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OFDM SMART BEAMFORMING

A Degree Thesis

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by

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Abstract

OFDM is the existing modulation technology used in mobile communications, which has been studied over the years to give new extensions of its principles in order to improve the communication performance to the end-users. Taking into account its knowledge, the thesis is focused on the 3GPP LTE Uplink Single Carrier-Frequency Division Multiple Access (SC-FDMA) transmission. The entire blocks within its system are simulated with Matlab in order to generate the signals transmitted by the user to the Base Station. Furthermore, the user needs to send data together with Demodulation Reference Signals (DM-RS) to adapt the beamformer algorithm at the receiver so that the antenna array point to a specific User Equipment cancelling the other interferences coming from other users. A non-blind adaptive algorithm by Wiener solution design is applied for Channel Estimation and minimizing the Minimum Square Error, which performs the smart operation of the system without interfering in the quality between users.

Resum

OFDM és la tecnologia existent en modulació per a les comunicacions mòbils, la qual ha sigut estudiada al llarg dels anys per donar noves extensions dels seus principis per tal de millorar les prestacions de comunicació als usuaris finals. Tenint en compte el seu coneixement, la tesis es centra en estudiar la transmissió 3GPP LTE SC-FDMA per al canal ascendent on tots els seus blocs han estat simulats amb Matlab per tal de generar les senyals transmeses de l'usuari a l'estació base. Per una altra banda, l'usuari necessita enviar informació conjuntament amb senyals de referència per adaptar l'algoritme de conformador de feix en el receptor per tal que el sistema d'antenes apunti a un usuari específic cancel·lant les interferències generades per altres usuaris. S'ha aplicat un algoritme adaptatiu no cec basat en la solució de Wiener per estimar el canal i minimitzar l'error quadràtic mig, el qual implementa l'operació intel·ligent del sistema per no interferir en la qualitat entre usuaris.

Resumen

OFDM es la tecnología existente en modulación para las comunicaciones móviles, la cual ha sido estudiada a lo largo de los años para dar nuevas extensiones de sus principios para poder mejorar las prestaciones de comunicación a los usuarios finales. Teniendo en cuenta su conocimiento, la tesis se centra en estudiar la transmisión 3GPP LTE SC-FDMA para el canal ascendente donde todos sus bloques han sido simulados con Matlab para generar las señales transmitidas del usuario a la estación base. Por otro lado, el usuario necesita enviar información conjuntamente con señales de referencia (DM-RS) para adaptar el algoritmo de conformador de haz en el receptor para que el sistema de antenas apunte a un usuario específico cancelando las interferencias generadas por otros usuarios. Se ha aplicado un algoritmo adaptativo no ciego basado en la solución de Wiener para estimar el canal y minimizar el error cuadrático medio, el cual implementa la operación inteligente del sistema para no interferir en la calidad entre usuarios.

Dedication

To my family. The reason for making me be who I am and my inspiration to never give up and to give the best of myself to achieve my goals. I couldn't have arrived at this point without you. Thank you for teaching me the most important lessons of my life.

To my friends and every single person who has become part of me these years. You have been the necessary support to enjoy day-to-day and life.

To all the teachers. Thank you for sharing all your knowledge and for giving me the opportunity to be a richer person.

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1. Introduction

1.1. State of the art

Multicarrier communication systems were first introduced in the 1960s, with the first OFDM patent being filed at Bell Labs in 1966. Initially only analogue design was proposed, using banks of sinusoidal signal generators and demodulators to process the signal for the multiple subchannels. In 1971, the use of the DFT was proposed, which made OFDM implementation cost-effective. Further complexity reductions were realized in 1980 by the application of the FFT.

OFDM then became the modulation of choice for many applications for both wired systems and wireless systems. Wireless applications benefit from the low complexity of the OFDM receiver, while not requiring a high-power transmitter in the consumer terminals. This avoids one of the main disadvantages of OFDM, namely that the transmitters tend to be more expensive because of the high PAPR.

The first cellular mobile radio system based on OFDM was proposed in 1985. Since then, the processing power of modern Digital Signal Processors has increased remarkably, paving the way for OFDM to be used in the 4G LTE. Here, the key benefits of OFDM, which come to the fore, are not only the low-complexity receiver but also the ability of OFDM to be adapted in a straightforward manner to operate in different channel bandwidths according to spectrum availability.

1.2. Objectives

The main goal of this project is to implement the physical layer through the OFDM transport signals, analysing section by section the full communication system based on the 3GPP LTE uplink in which there is applied an adaptive beamformer implementation to estimate the channel for giving an overview of the quality in the system between different users when multipath appears. The methodology is based on Matlab simulations taking into account the multiple technique access, in particular the SC-FDMA in comparison with the OFDMA used in the downlink. Therefore, different signals are transmitted to the BS where the smart antenna array design is studied within the SDMA method to adapt the beamforming for a specific user. The objective is to obtain highest gain in his direction and cancelling the interferences coming from the other users trying to connect, which has to be reflected on the radiation pattern. On the other hand, another important aspect that has to be studied is the relation between the RS and CE, proving it together with Wiener solution as a non-blind adaptive beamforming algorithm example to perform the smart operation of the system.

In addition, there are proposed two different demodulation processes in order to carry out the study: point-to-point communication and time reference beamforming. These results will be presented in terms of BER using the Monte Carlo method.

1.3. Thesis background

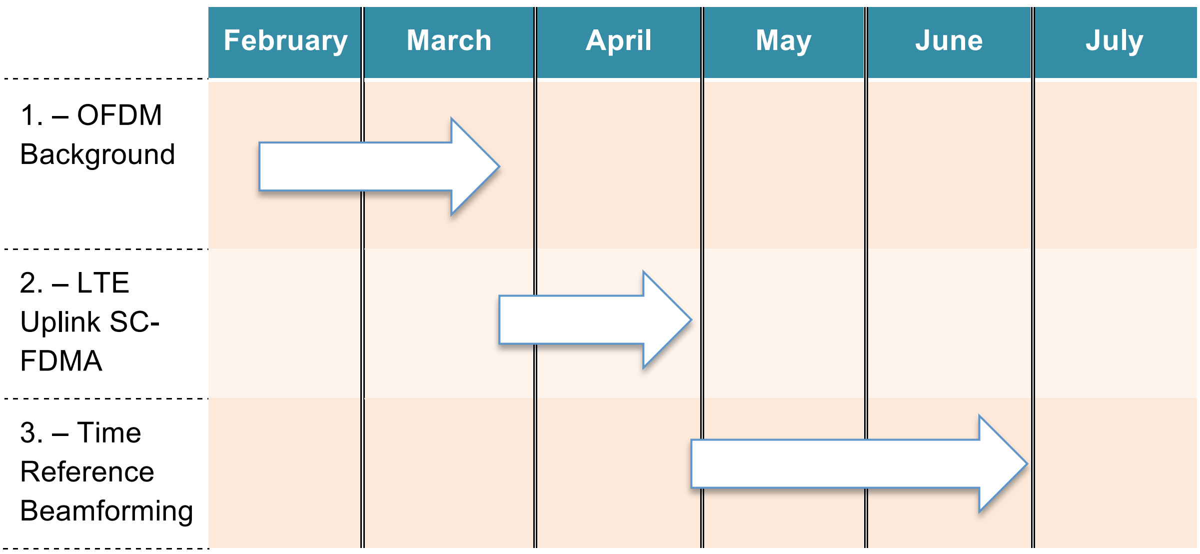
The project begins on February 2018 from the proposal of Ana I. Pérez to take a close look on the subject.

The methodology is based on Matlab simulations to analyse step by step the different signals and blocks that take part in the process. All code is created right from the start, excepting the generation of the beamforming pattern, which has been adapted from the software created by Miguel A. Lagunas that is available on the webpage of the CTTC.

The main objective has been reduced to understanding all the uplink process. Due to the large extension of the topic together with having a work experience at the same time has narrowed down a bit the initial plan. Although different receivers can be implemented, the project focuses on the principles of a smart design.

The requirements and specifications of the thesis are related to the expected results from simulations, understanding the mathematical model that takes part in the system to be accurate in the conclusion of each section.

The principal work packages taken on the project are shown in the following Gantt diagram:



Each work package presents different tasks with the corresponding milestones:

Table 1.1 Work plan structure

WP#	Task#	Short title	Milestone / deliverable	Date (week)
1	1	OFDM point-to-point communication	Simulate the “simple” OFDM receiver and transmitter with all the corresponding blocks. Achieve BER representation.	6
2	1	SC-FDMA point-to-point communication	Simulate uplink LTE signal generation for different users in the scenario. Achieve BER representation.	11
3	1	Smart Antenna Array design	Transmit a subframe with reference signals generation and perform the environment design to calculate the covariance matrix for the beamforming.	15
3	2	Beamforming pattern	Check that the system points correctly to a specific user cancelling the interferences coming from other users.	16
3	3	Demodulation Time Reference Beamforming	Design the Wiener Solution algorithm that allows channel estimation and achieve BER representation.	17

2. OFDM

2.1. Orthogonal Multiplexing Principle

The basic idea of OFDM is to divide a data stream into multiple substreams to be transmitted over different orthogonal subchannels centered at different subcarrier frequencies. The number of substreams is chosen to make the symbol time on each substream much greater than the delay spread of the channel. This insures that the substreams will not experience significant ISI.

2.2. OFDM System

Figure 2.1 shows the typical block diagram of an OFDM system:

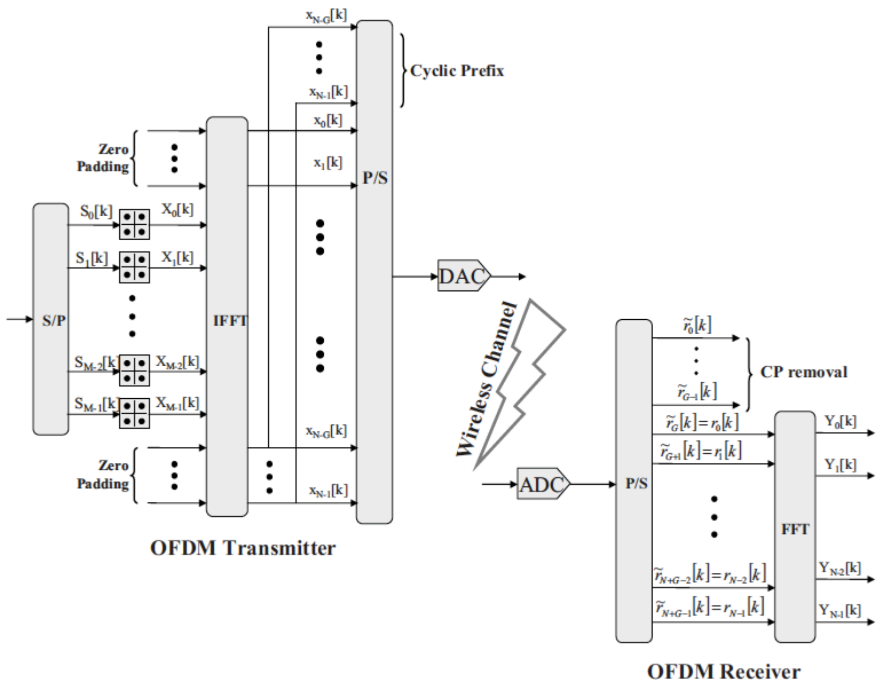


Figure 2.1 OFDM system model [1]

The signal to be transmitted is defined in the frequency domain. A Serial-to-Parallel (S/P) converter collects serial data symbols into a data block $S[k] = \left[S_0[k], S_1[k], \dots, S_{M-1}[k]\right]^T$ of dimension *M*, where k is the index of an OFDM symbol (spanning *M* subcarriers). The *M* parallel data streams are first independently modulated with possibility to use different modulations (QPSK, 16QAM, 64QAM…), resulting in the complex vector $X[k] = \left[X_0[k], X_1[k], \dots, X_{M-1}[k]\right]^T$. Due to channel frequency selectivity, the channel gain may differ between subcarriers, and thus some can carry higher data-rates than others. Then, the vector $X[k]$ is used as input to an N-point IFFT resulting in a set of N complex time-domain samples $x[k] = \left[x_0[k], \dots, x_{N-1}[k]\right]^T$. In a practical OFDM system, the number of processed subcarriers is greater than the number of modulated subcarriers (i.e. $N \geq M$), with the un-modulated subcarriers being padded with zeros.

The next key operation is the creation of a guard period at the beginning of each OFDM symbol $x[k]$ by adding a Cyclic Prefix (CP), to eliminate the remaining impact of ISI caused by multipath propagation. The CP is generated by duplicating the last *G* samples of the IFFT output and appending them at the beginning of $x[k]$ as shown in Figure 2.2. This yields the time domain OFDM symbol $\left[x_{N-G}[k], \dots, x_{N-1}[k], x_0[k], \dots, x_{N-1}[k]\right]^T$ to be transmitted through the wireless channel.

Moreover, to avoid ISI completely, the CP length *G* must be chosen to be longer than the longest channel impulse response to be supported. The CP converts the linear convolution of the channel into a circular one, which is suitable for DFT processing, transforming into a multiplicative operation in the frequency domain. Hence, the transmitted signal over a frequency-selective (i.e. multipath) channel is converted into a transmission over *N* parallel flat-fading channels in the frequency domain. As a result, the equalization consists of just one complex multiplication per subcarrier.

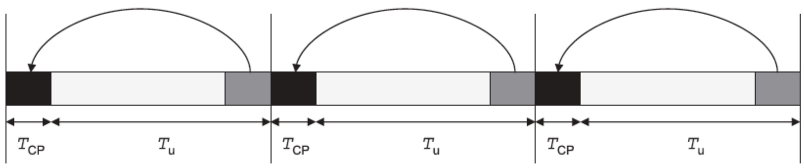


Figure 2.2 CP insertion [1]

Finally, the time domain OFDM symbol is Parallel-to-Serial (P/S) converted for transmission through the frequency-selective channel $h_m[k]$.

At the receiver, the reverse operations are performed to demodulate the OFDM signal. The received discrete-time OFDM symbol k including CP, can be expressed as:

$$\tilde{r} = \begin{bmatrix} \tilde{r}_0[k] \\ \tilde{r}_1[k] \\ \vdots \\ \tilde{r}_{G-2}[k] \\ \tilde{r}_{G-1}[k] \\ \tilde{r}_G[k] \\ \vdots \\ \tilde{r}_{N+G-1}[k] \end{bmatrix} = A \cdot \begin{bmatrix} h_0[k] \\ h_1[k] \\ \vdots \\ h_{G-1} \end{bmatrix} + \begin{bmatrix} w_0[k] \\ w_1[k] \\ \vdots \\ w_{G-2}[k] \\ w_{G-1}[k] \\ \tilde{z}_G[k] \\ \vdots \\ w_{N+G-1}[k] \end{bmatrix} \tag{2.1}$$

where w_m is the additive noise and

$$A = \begin{bmatrix} x_{N-G}[k] & x_{N-1}[k-1] & x_{N-2}[k-1] & \cdots & x_{N-G-1}[k-1] \\ x_{N-G+1}[k] & x_{N-G}[k] & x_{N-1}[k] & \cdots & x_{N-G+2}[k-1] \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ x_{N-2}[k] & x_{N-3}[k] & \ddots & x_{N-G}[k] & x_{N-1}[k-1] \\ x_{N-1}[k] & x_{N-2}[k] & \ddots & x_{N-G+1}[k] & x_{N-G}[k] \\ x_0[k] & x_{N-1}[k] & \ddots & x_{N-G+2}[k] & x_{N-G+1}[k] \\ \vdots & \cdots & \cdots & \cdots & \vdots \\ x_{N-1}[k] & x_{N-2}[k] & \cdots & \cdots & x_{N-G}[k] \end{bmatrix}$$

The elements correspond to

$$x_m[k] = \frac{1}{\sqrt{N}} \sum_{n=1}^{N} X_n[k]\, e^{\frac{2j\pi mn}{N}} \tag{2.2}$$

In reverse, the frequency-domain signal $X_n[k]$ can be obtained by

$$X_n[k] = \frac{1}{\sqrt{N}} \sum_{m=1}^{N} x_m[k]\, e^{\frac{-2j\pi mn}{N}} \tag{2.3}$$

Assuming that time- and frequency-synchronization is achieved, a number of samples corresponding to the length of the CP are removed, such that only and ISI-free block of samples if passed to the DFT. If the number of subcarriers *N* is designed to be a power of 2, a highly efficient FFT implementation may be used to transform the signal back to the frequency domain. Among the *N* parallel streams output from the FFT, the modulated subset of *M* subcarriers are selected and further processed by the receiver.

2.3. Practical OFDM System: LTE case

As discussed in section 2.2, the principal advantage of OFDM is the strong reduction in ISI when a multipath propagation environment is presented. A channel that meets these requirements is given in a mobile propagation environment as shown in Figure 2.3 so it is typically time dispersive and frequency selective: multiple replicas of a transmitted signal are received with various time delays and due to multipath resulting from reflections, the signal incurs along the path between the transmitter and receiver.

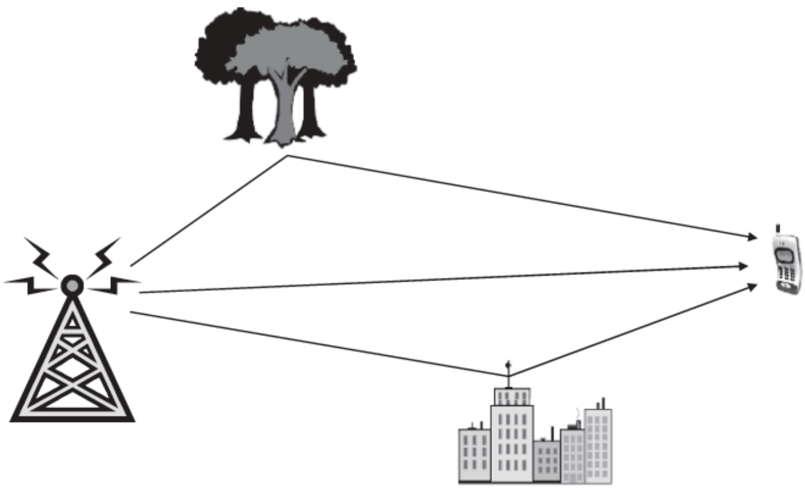


Figure 2.3 Multipath propagation [2]

The practical OFDM system presented in the project is LTE, which considers that simultaneous users are transmitting/receiving at the same time. For that, it is important to establish access techniques. The main advantages of using OFDM in a mobile access system are the following:

1. Long symbol time and guard interval increases robustness to multipath and limits ISI.
2. Eliminates the need for intra-cell interference cancellation.
3. Allows flexible utilization of frequency spectrum.
4. Increases spectral efficiency due to orthogonality between subcarriers.
5. Allows optimization of data rates for all users in a cell by transmitting on the best subcarriers for each user.

The last feature is the fundamental aspect of Orthogonal Frequency Division Multiple Access (OFDMA): the use of OFDM technology to multiplex traffic by allocating specific patterns of subcarriers in the time-frequency space to different users.

The downlink physical layer of LTE is based on OFDMA. However, despite its many advantages, OFDMA has certain drawbacks such as high sensitivity to frequency offset (resulting from instability of electronics and Doppler spread due to mobility) and high Peak-to-Average Power Ratio (PAPR). PAPR occurs due to random constructive addition of subcarriers and results in spectral spreading of the signal leading to adjacent channel interference. It is a problem that can be overcome with high compression point power amplifiers and amplifier linearization techniques. While these methods can be used on the base station, they become expensive on the User Equipment (UE). Hence, LTE uses Single Carrier-Frequency Division Multiple Access (SC-FDMA) with cyclic prefix on the uplink, which reduces PAPR as there is only a single carrier as opposed to *N* carriers. Figure 2.4 illustrates the concepts of OFDMA and SC-FDMA.

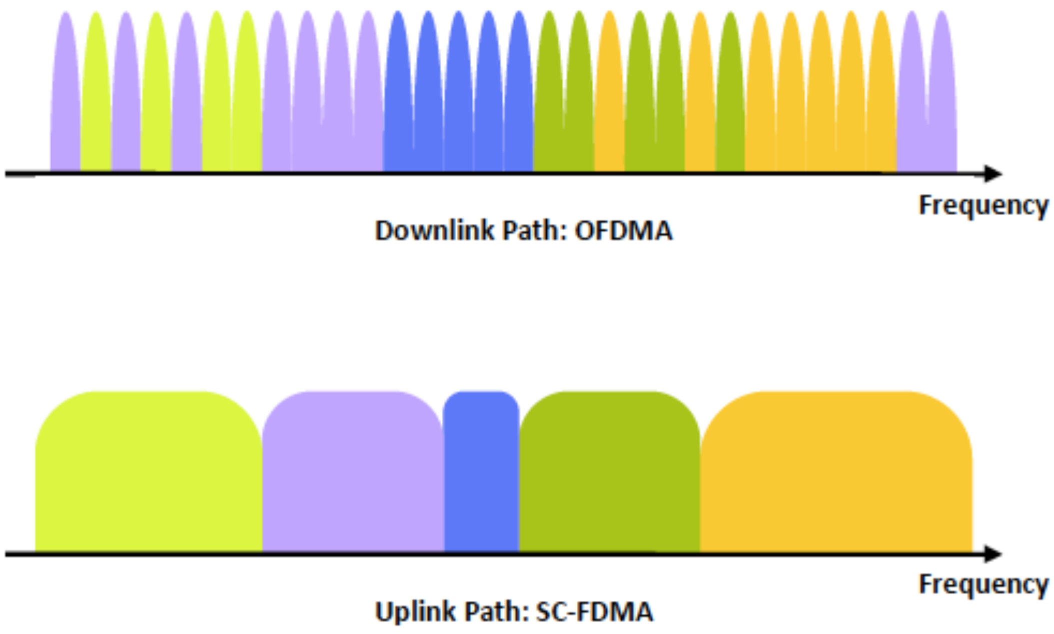


Figure 2.4 Frequency Domain Representations of Downlink and Uplink LTE Access Technologies [1]

In the next chapter, SC-FDMA will be presented in detail to focus the work on the uplink physical layer of LTE.

3. SC-FDMA

3.1. SC-FDMA Principles

Like OFDM, SC-FDMA divides the transmission bandwidth into multiple parallel subcarriers, maintaining orthogonality by the use of a CP, which prevents ISI between SC-FDMA information blocks. It transforms the linear convolution of the multipath channel into a circular one, enabling the receiver to equalize the channel simply by scaling each subcarrier by a complex gain factor.

However, unlike OFDM, where the data symbols directly modulate each subcarrier independently (such that the amplitude of each subcarrier at a given time instant is set by the constellation points of the digital modulation scheme), in SC-FDMA the signal modulated onto a give subcarrier is a linear combination of all the data symbols transmitted at the same time instant. Thus in each symbol period, all the transmitted subcarriers of a SC-FDMA signal carry a component of each modulated data symbol. This gives its crucial single-carrier property, which results in the PAPR being significantly lower than pure multicarrier transmission schemes such as OFDM.

3.2. SC-FDMA Signal Processing

A SC-FDMA signal can be generated in either the time domain or the frequency domain. Although both techniques are dual and functionally equivalent, the time-domain generation is less bandwidth efficient due to time-domain filtering. Therefore, frequency-domain signal generation structure is presented as follows in Figure 3.1.

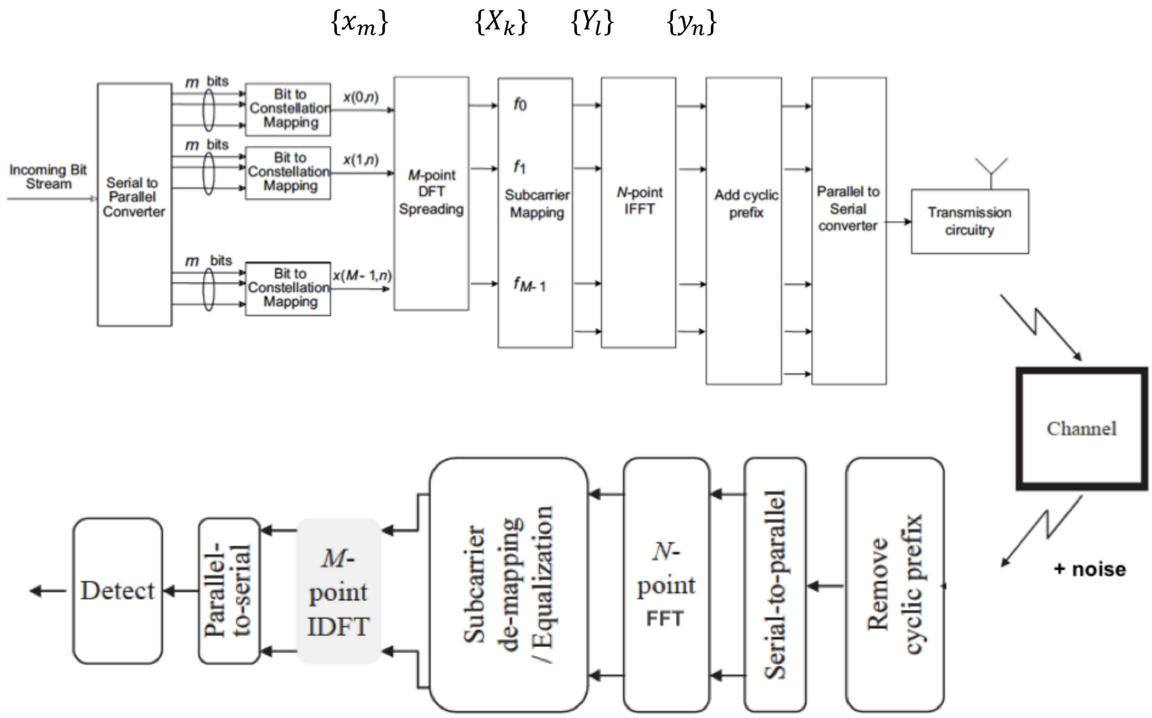


Figure 3.1 Transmitter and receiver structure of SC-FDMA for frequency-domain processing

The system consists of sending one block of data divided into *M* blocks of *m* bits. The first step is to perform an *M*-point DFT operation on each block of *M* QAM data symbols. Zeros are then inserted among the outputs of the DFT in order to match the DFT size to an *N*-subcarrier modulator (IFFT). The zero-padded DFT output is mapped to the *N* subcarriers, with the position of the zeros determining to which subcarriers the DFT-precoded data is mapped. Finally, the transmitter inserts a CP.

The relation between *N* and *M* denotes the bandwidth spreading factor Q, which determines the users allowed within the system.

$$Q = \frac{N}{M} \tag{3.1}$$

Then, the SC-FDMA system can handle up to *Q* orthogonal source signals with each source occupying a different set of *M* orthogonal subcarriers. In the notation of Figure 3.1, x_m (m=0,1,…,M-1) represents modulated source symbols and X_k (k=0,1,…,M-1) represents *M* samples of the DFT of x_m. Y_l (l=0,1,…,N-1) represents the frequency domain samples after subcarrier mapping and y_n (n=0,1,…,N-1) represents the transmitted time domain symbols to the channel obtained from IFFT of Y_l. The subcarrier mapping block assigns frequency domain modulation symbols to subcarriers (see Section 3.3), which is also referred to as *scheduling*.

In the same way, the receiver operates the opposite signal processing. The DFT transforms the received signal to the frequency domain in order to recover N subcarriers. The de-mapping operation isolates the M frequency domain samples of each source signal. Because SC-FDMA uses single carrier modulation, it encounters substantial linear distortion manifested as ISI, which is cancelled by the frequency domain equalizer. At the end, the IDFT transforms equalized symbols back to the time domain where a detector produces the received sequence of M modulation symbols.

3.3. Subcarrier Mapping

There are presented two methods of assigning the M frequency domain modulation symbols to subcarriers: *distributed* subcarrier mapping and *localized* subcarrier mapping.

As illustrated in the example of Figure 3.2 and 3.3 where M = 4 symbols per block, N = 12 subcarriers and Q = N/M = 3 users, the modulated symbols are equally spaced across the entire channel bandwidth in the distributed mode. On the other hand, the symbols are assigned to M adjacent subcarriers in the localized mode. In both modes, the IFFT in the transmitter assigns zero amplitude to the N - M unoccupied subcarriers. The localized subcarrier mapping mode is referred to LFDMA and the distributed mapping mode as DFDMA. The case of N = Q x M for the distributed mode with equidistance between occupied subcarriers is referred to as Interleaved (IFDMA). IFDMA is a special case and it is very efficient in that the transmitter can modulate the signal strictly in the time domain without the use of DFT and IFFT, so it is reduced to a single complex multiplication equivalent to a phase rotation of each modulation symbol at the input to the transmitter. Therefore, IFDMA and LFDMA are compared in the thesis.

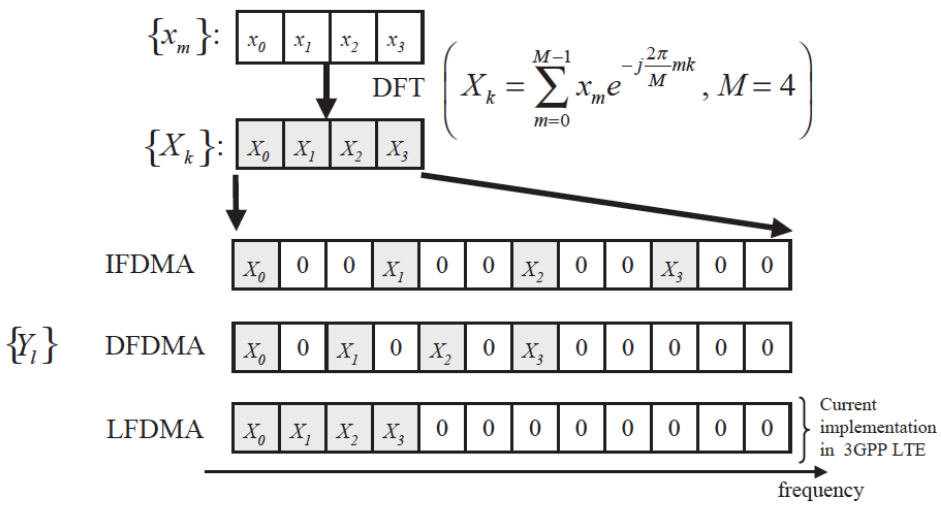


Figure 3.2 Subcarrier mapping example [2]

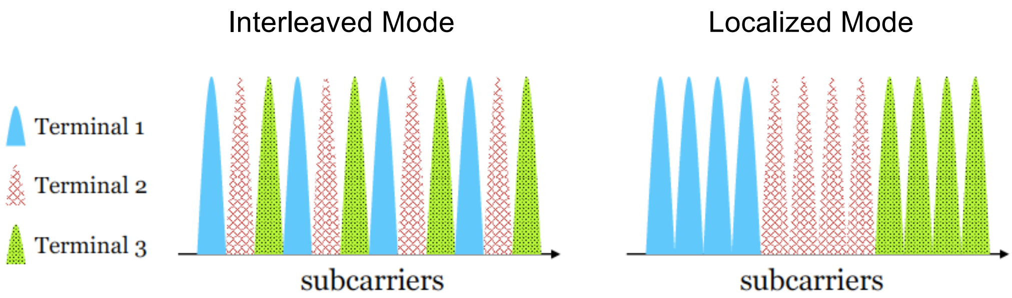


Figure 3.3 Subcarrier allocation [2]

3.3.1. Time Domain Symbols of IFDMA

For IFDMA, the aforementioned combination of the DFT and IDFT is reduced to the multiplication of each input symbol by a complex number with a phase rotation resulting in $\exp\left(\frac{j2\pi rn}{N}\right)$, where *N* is the number of points in the inverse transform, *r* is the amount of the frequency shift and *n* is the output sample number in the time domain.

The mathematical formulas corresponding to this description begin with frequency domain symbols Y_l:

$$Y_l = \begin{cases} X_{l/Q}, & l = Q \cdot k \ \ (0 \le k \le M-1) \\ 0, & otherwise \end{cases} \tag{3.1}$$

where $0 \le l \le N-1$ and $N = Q \cdot M$.

Let $n = M \cdot q + m$ $(0 \le q \le Q-1, 0 \le m \le M-1)$. Then,

$$\begin{aligned} y_n &= (y_{Mq+m}) \\ &= \frac{1}{N}\sum_{l=0}^{N-1} Y_l e^{\frac{j2\pi nl}{N}} = \frac{1}{N}\sum_{l=0}^{N-1} X_{\frac{l}{Q}} e^{\frac{j2\pi nl}{N}} = \frac{1}{Q}\cdot\frac{1}{M}\sum_{k=0}^{M-1} X_k e^{j2\pi\left(\frac{n}{QM}\right)Qk} \\ &= \frac{1}{Q}\cdot\frac{1}{M}\sum_{k=0}^{M-1} X_k e^{j2\pi\left(\frac{Mq+m}{M}\right)k} = \frac{1}{Q}\cdot\left(\frac{1}{M}\sum_{k=0}^{M-1} X_k e^{\frac{j2\pi mk}{M}}\right) = \frac{1}{Q}x_m = \frac{1}{Q}x_{(n)_{mod\,M}} \end{aligned} \tag{3.2}$$

The resulting time symbols $\{y_n\}$ are simply a repetition of the original input symbols $\{x_m\}$ with a scaling factor of $1/Q$ in the time domain.

When the subcarrier allocation starts from the *r*-th subcarrier $(0 < r \le Q-1)$, then,

$$Y_l = \begin{cases} X_{\frac{l}{Q}-r}, & l = Q \cdot k + r \ (0 \le k \le M-1) \\ 0, & otherwise \end{cases} \tag{3.3}$$

Corresponding to Equation (3.3), the time symbols $\{y_n\}$ can be derived as:

$$y_n = \frac{1}{Q} x_{(n)_{mod\,M}} \cdot e^{\frac{j2\pi rn}{N}} \tag{3.4}$$

3.3.2. Time Domain Symbols of LFDMA

For LFDMA, the frequency samples after subcarrier mapping $\{Y_l\}$ can be described as follows:

$$Y_l = \begin{cases} X_l, & 0 \leq l \leq M-1 \\ 0, & M \leq l \leq N-1 \end{cases} \tag{3.5}$$

Let $n = Q \cdot m + 1$, where $0 \leq m \leq M-1$, $0 \leq q \leq Q-1$, and $N = Q \cdot M$. Then:

$$y_n = y_{Qm+q} = \frac{1}{N} \sum_{l=0}^{N-1} Y_l e^{\frac{j2\pi nl}{N}} = \frac{1}{Q} \cdot \frac{1}{M} \sum_{l=0}^{M-1} X_l\, e^{j2\pi\left(\frac{Qm+q}{QM}\right)l} \tag{3.6}$$

If $q = 0$, then:

$$y_n = y_{Qm} = \frac{1}{Q} \cdot \frac{1}{M} \sum_{l=0}^{M-1} X_l e^{j2\pi\left(\frac{Qm}{QM}\right)l} = \frac{1}{Q} \cdot \frac{1}{M} \sum_{l=0}^{M-1} X_l e^{j2\pi\left(\frac{m}{M}\right)l} = \frac{1}{Q} x_m = \frac{1}{Q} x_{n_{mod\,M}} \tag{3.7}$$

If $q \neq 0$, since $X_l = \sum_{p=0}^{M-1} x_p e^{-\frac{j2\pi pl}{M}}$, then Equation (3.6) can be expressed as follows:

$$y_n = y_{Q\cdot m+q} = \frac{1}{Q} \cdot \frac{1}{M} \sum_{l=0}^{M-1} X_l\, e^{j2\pi\left(\frac{Qm+q}{Q\cdot M}\right)l} = \frac{1}{Q} \cdot \frac{1}{M} \sum_{l=0}^{M-1} \left(\sum_{p=0}^{M-1} x_p e^{-\frac{j2\pi pl}{M}} \right) e^{j2\pi\left(\frac{Qm+q}{Q\cdot M}\right)l}$$

$$= \frac{1}{Q} \cdot \frac{1}{M} \sum_{l=0}^{M-1} \sum_{p=0}^{M-1} x_p e^{j2\pi\left\{\frac{m-p}{M}+\frac{q}{Q\cdot M}\right\}l} = \frac{1}{Q} \cdot \frac{1}{M} \sum_{p=0}^{M-1} x_p \left(\sum_{l=0}^{M-1} e^{j2\pi\left\{\frac{m-p}{M}+\frac{q}{Q\cdot M}\right\}l} \right)$$

$$= \frac{1}{Q} \cdot \frac{1}{M} \sum_{p=0}^{M-1} x_p \frac{1 - e^{j2\pi(m-p)} e^{j2\pi\frac{q}{Q}}}{1 - e^{j2\pi\left\{\frac{m-p}{M} + \frac{q}{Q \cdot M}\right\}}} = \frac{1}{Q} \cdot \frac{1}{M} \sum_{p=0}^{M-1} x_p \frac{1 - e^{j2\pi\frac{q}{Q}}}{1 - e^{j2\pi\left\{\frac{m-p}{M} + \frac{q}{Q \cdot M}\right\}}} \tag{3.8}$$

$$= \frac{1}{Q} \cdot \left(1 - e^{j2\pi\frac{q}{Q}}\right) \cdot \frac{1}{M} \sum_{p=0}^{M-1} \frac{x_p}{1 - e^{j2\pi\left\{\frac{m-p}{M} + \frac{q}{Q \cdot M}\right\}}}$$

Thus,

$$y_n = y_{Q \cdot m + q} = \begin{cases} \frac{1}{Q} x_{n_{mod\, M}}, & q = 0 \\ \frac{1}{Q} \cdot \left(1 - e^{j2\pi\frac{q}{Q}}\right) \cdot \frac{1}{M} \sum_{p=0}^{M-1} \frac{x_p}{1 - e^{j2\pi\left\{\frac{m-p}{M} + \frac{q}{Q \cdot M}\right\}}}, & q \neq 0 \end{cases} \tag{3.9}$$

3.4. Subcarrier De-mapping

Before performing the basic SC-FDMA demodulation process, the base station separates the users in the frequency domain during the subcarrier de-mapping process as shown in Figure 3.4. The process consists in getting the proper subcarriers following the same criteria of $\{Y_l\}$ described in Section 3.3 for each specific mode.

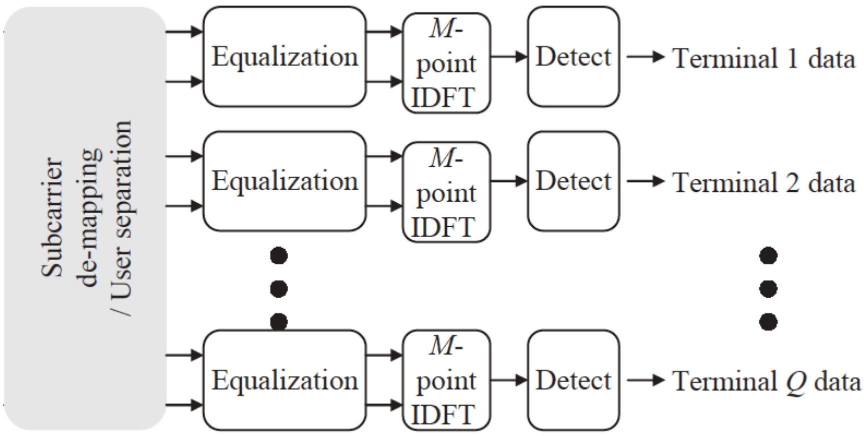


Figure 3.4 User separation

3.5. SC-FDMA Design in LTE

Having outlined the key principles of SC-FDMA transmission, the following section explains the application of SC-FDMA to the LTE uplink.

3.5.1. Uplink Time and Frequency Structure

LTE specifies signal transmission in six possible channel bandwidths ranging from 1.4 to 20 MHz as shown in Table 3.1. Each channel is divided into frequency bands of 15 kHz, each specified by a subcarrier frequency.

Moreover, data is sent through 10 ms radio frames divided into 20 slots, numbered from 0 to 19, each of duration 0.5 ms for frequency division duplex (FDD) transmissions. A consecutive pair of slots starting with an even-numbered slot is referred to as a subframe. The 1 ms duration of a subframe is a LTE transmission time interval (TTI). With FDD transmissions, all the slots can carry uplink physical channels or reference signals. The FDD frame structure is referred to as frame structure type 1.

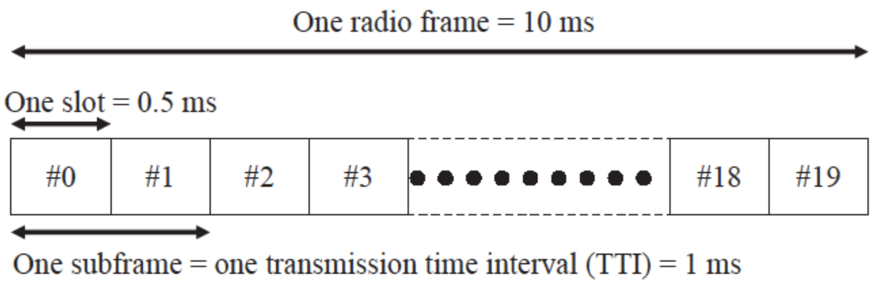


Figure 3.5 Frame structure type 1 (FDD) [2]

On the contrary, the situation is more complicated for time division duplex (TDD) transmission because the uplink and downlink transmissions share the same frequency band. Because of that, the thesis will only study FDD transmissions characteristics.

Table 3.1 LTE Uplink SC-FDMA parameterization

	Channel bandwidth (MHz)					
	1.4	3	5	10	15	20
FFT size	128	256	512	1024	1536	2048
Sampling rate [MHz]	1.92	3.84	7.68	15.36	23.04	30.72
Number of occupied subcarriers	72	180	300	600	900	1200
Number of RBs	6	15	25	50	75	100
Samples per slot	960	1920	3840	7680	11520	15360

A resource grid as illustrated in Figure 3.6 describes the transmitted signal in each slot, where are assigned to physical channels in time-frequency units referred to as Resource Blocks (RBs). A resource block has a duration of 0.5 ms (one slot) and a bandwidth of 180 kHz (12 subcarriers).

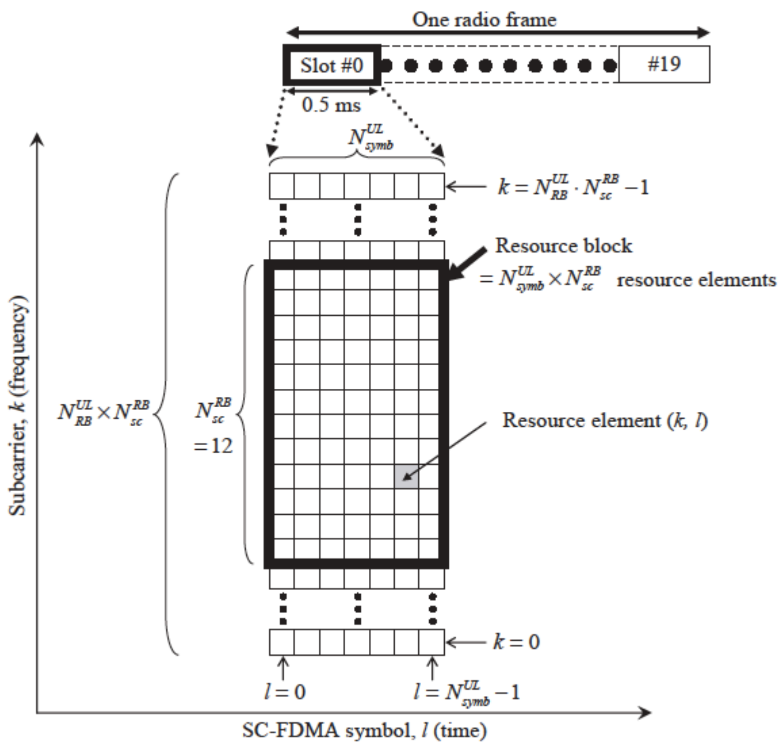


Figure 3.6 Uplink Resource Grid [2]

In the time domain, each uplink slot carries six or seven SC-FDMA symbols depending on the applied cyclic prefix: normal or extended; as shown in Table 3.2.

Table 3.2 Normal and Extended Cyclic Prefix for a 20 MHz channel bandwidth

	Normal CP	Extended CP
SC-FDMA symbols per RB	7	6
Duration the CP (samples)	160 (symbol 0) 144 (symbols 1-6)	512 (all six symbols); 25% of the total symbol
Duration of the CP (sec)	≈5.21 μs (symbol 0) ≈4.69 μs (symbols 1-6)	≈16.67 μs (all six symbols)

3.5.2. Uplink Reference Signals

The LTE SC-FDMA uplink incorporates Reference Signals (RSs) for data demodulation and channel sounding. The roles of the uplink RSs include enabling channel estimation to aid coherent demodulation at the base station, channel quality estimation for uplink scheduling, power control, timing estimation and direction-of-arrival estimation to support downlink beamforming. The thesis will be focused on the study of coherent demodulation with channel estimation for beamforming receiver applications.

Then, two types of RS are supported on the uplink:

- *DeModulation RS (DM-RS)*, associated with transmission of uplink data on the Physical Uplink Shared Channel (PUSCH) and/or control signalling on the Physical Uplink Control Channel (PUCCH). These RSs are primarily used for channel estimation for coherent demodulation.
- *Sounding RS (SRS)*, not associated with uplink data and/or control transmissions, and primarily used for channel quality determination to enable frequency-selective scheduling on the uplink.

These RSs are based on Zadoff-Chu (ZC) sequences, which are non-binary unit-amplitude sequences that satisfy a Constant Amplitude Zero Autocorrelation (CAZAC) property. The ZC sequence of odd-length N_{ZC} is given by:

$$a_q(n) = \exp\left[-j2\pi q \frac{\frac{n(n+1)}{2}+ln}{N_{ZC}}\right] \tag{3.10}$$

where $q \in \{1, \dots, N_{ZC} - 1\}$ is the ZC sequence root index, $n = 0, 1, \dots, N_{ZC} - 1$, $l \in \mathbb{N}$ is any integer. In LTE, $l = 0$ is used for simplicity and N_{ZC} is selected to be the largest prime number smaller than or equal to the RS sequence length N_p, which is equal to the number of assigned subcarriers M_{sc}^{RS}, being a multiple of the number of subcarriers per RB.

$$N_p = M_{sc}^{RS} = m \cdot N_{sc}^{RB}, \quad 1 \leq m \leq N_{RB}^{UL} \tag{3.11}$$

The ZC sequence of length N_{ZC} is then cyclically extended to the largest length N_p as follows:

$$\tilde{r}_q(n) = a_q(n \, mod \, N_{ZC}), \quad n = 0, 1, \dots, Np - 1 \tag{3.12}$$

These sequences satisfy:

- Constant amplitude in the frequency domain for equal excitation of all the allocated subcarriers for unbiased channel estimates.
- Low Cubic Metric (CM) in the time domain for enabling the transmission power of the RSs to be boosted at the cell-edge.
- Ideal cyclic autocorrelation for accurate channel estimation.
- Optimal cross-correlation properties between different RSs to reduce interference from RSs transmitted on the same resources in other cells.

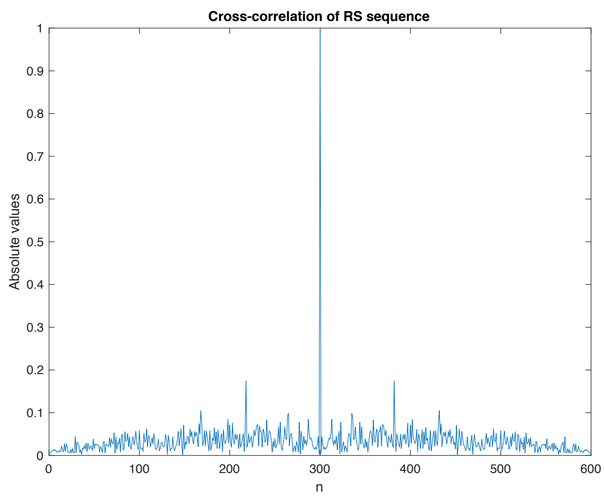


Figure 3.7 ZC Properties Impact on RSs

Following the explanation in Section 3.2, the RS has to be generated for transmission with the particularity of no DFT spreading application as shown in Figure 3.8.

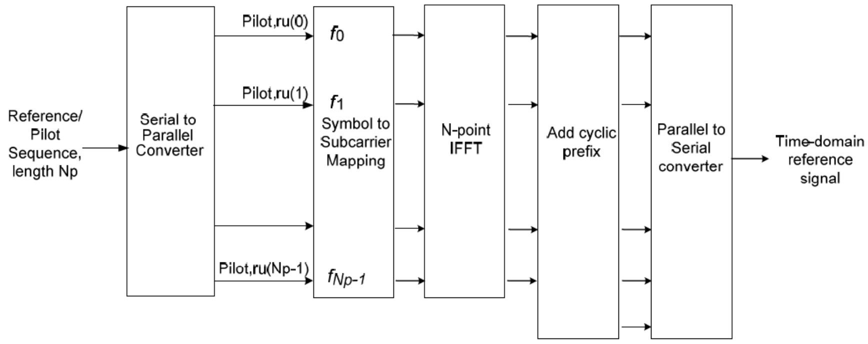


Figure 3.8 Transmitter structure for SC-FDMA reference signals [1]

As aforementioned, the thesis will focus on Demodulation Reference Signals. This signal will be mapped to the 4th SC-FDMA symbol of the slot during normal cyclic prefix and to every 3rd SC-FDMA symbol during extended cyclic prefix. This resource mapping is shown in the following figure.

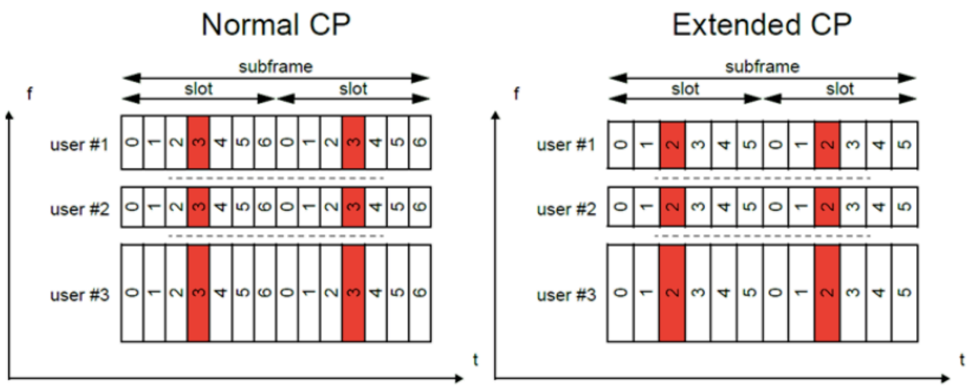


Figure 3.9 Reference Signal allocation

Finally, there has to be considered the case of the UEs' assignment for transmitting on the same RBs, as it corresponds to the practical case of uplink multi-user MIMO (sometimes also referred to as Spatial Division Multiple Access (SDMA) or 'Virtual MIMO'). In these situations, the RSs can interfere with each other, and some means of separating the RSs from the different transmitters is required. Using different base sequences for different UEs transmitting in the same RBs is not ideal due to the non-zero cross-correlation between the base sequences which can degrade the channel estimation at the eNodeB. It is preferable that the RS signals are fully orthogonal.

Therefore in LTE, orthogonality between RSs occupying the same RBs is instead provided by exploiting the fact the correlation of a ZC sequence with any Cyclic Shift (CS) of the same sequence is zero. As the channel impulse response is of finite duration, different transmitters can use different cyclic time shifts of the same base RS sequence, with the RSs remaining orthogonal provided that the CSs are longer than the channel impulse response.

If the RS SC-FDMA symbol duration is T_p and the channel impulse response duration is less than T_{cs}, then up to T_p/T_{cs} different transmitter can transmit in the same symbol, with different cyclic shifts values, with separable channel estimates at the receiver. For example, Figure 3.9 shows that if $T_p/T_{cs} = 4$ and there are four transmitters, then each transmitter can use a cyclic of the same base sequence. At the receiver, by correlating the received signal from the different transmitters occupying the same RBs with the base sequence, the channel estimates from the different transmitters are separable in the time domain.

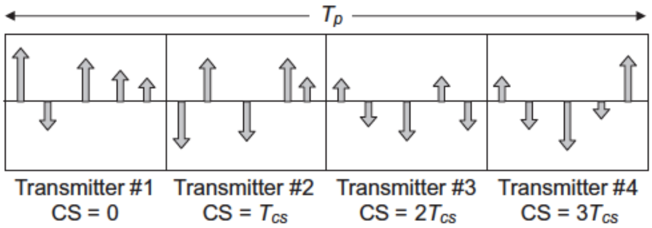


Figure 3.10 CS of RS signals [1]

Since a cyclic time shift is equivalent to applying a phase ramp in frequency domain, the representation of a base sequence with CS, α, is given by:

$$r_{u,v}^{(\alpha)}(n) = e^{j\alpha n}\,\tilde{r}_{u,v}(n) \tag{3.13}$$

where *u* is the sequence-group with base sequence *v*, $\alpha = 2\pi n_t/P$ with n_t the cyclic time shift index for transmitter *t* and *P* the number of equally spaced CS supported.

4. Beamforming

4.1. Introduction

In beamforming, multiple transmit antennas can be used to shape the overall antenna radiation pattern (or the beam) in order to maximize the overall antenna gain in the direction of a specific mobile terminal. In other words, the multiple transmit antennas correspond to the different users trying to connect to the BS and therefore it has to point to a specific user cancelling the interferences coming from the other ones.

The use of beamforming techniques can lead to an increase in the signal power at the receiver proportional to the number of transmit antennas. Typically, beamforming relies on the use of an antenna array of at least eight antenna elements. Beamforming is then implemented by applying different complex-valued gains (otherwise known as weights) to different elements of the antenna array. The overall transmission beam can then be steered in different directions by applying different phase shifts to the signals on the different antennas.

The LTE standard specifies neither the number of antennas in the antenna array nor the algorithms that are to be used in adjusting the complex-valued gains applied to each array element. The LTE specification refers to an antenna port 5, which represents the virtual antenna port created by the use of beamforming techniques. UE-specific reference signals are used for channel estimation. Since mutually orthogonal reference signals are generated scheduled on the same pairs of resource blocks, different UEs can resolve their allocated reference signals and use them for equalization and demodulation.

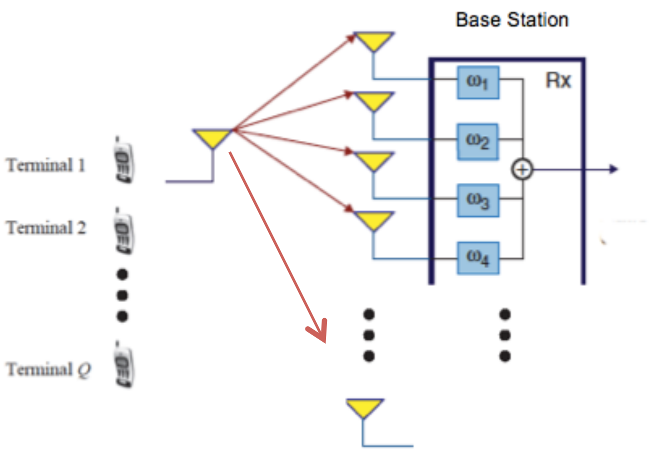


Figure 4.1 Beamforming overview

4.2. Signal Aperture Model

The contribution of all the signals arriving to the base station at a certain instant is defined as Snapshot, which considers the sum of each source waveform with a particular direction of arrival plus noise addition:

$$\underline{X_n} = \sum_{s=1}^{NS} a_s(n) \cdot \underline{S_s} + \underline{n_n} \tag{4.1}$$

where *NS* corresponds to the number of sources, $a_s(n)$ the corresponding source waveform, $\underline{S_s}$ the corresponding Steering vector and $\underline{n_n}$ the additive noise vector.

On the other hand, it has to be considered the antenna array system design, which is defined within the Steering vector as:

$$\underline{S_s} = \frac{2\pi f_c}{c} \cdot \underline{d} \cdot \sin(\theta_s) \tag{4.2}$$

where f_c is the central frequency, *c* the velocity of propagation, θ_s elevation of the corresponded source and $\underline{d}$ is the distance of sensors in wavelengths to the phase centre vector. All receiving antennas are designed to be at a distance of 0.5λ between each other's.

4.3. Time Reference Beamforming (TRB)

The Time Reference Beamforming (TRB) is reduced to a non-blind adaptive algorithm based on Wiener's solution in order to minimize the MSE as shown in Figure 4.2. The beamformer $\underline{w}$ selects the direction or directions where there is the desired source emitting the reference signal.

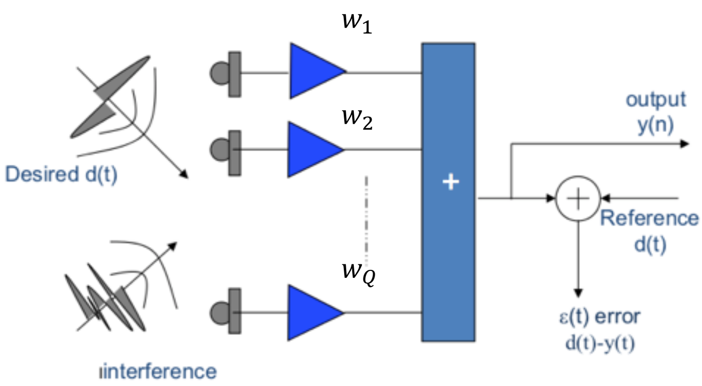


Figure 4.2 TRB Design [8]

If the error power is presented as:

$$\varepsilon = E[\varepsilon(n) \cdot \varepsilon^*(n)] = E[|d(n) - y(n)|^2] = E\left[\left|d(n) - \underline{w}^H \cdot X_n\right|^2\right]$$
$$= E\left[d(n)d^*(n) + \underline{w}^H \underline{X_n} \underline{X_n^H} \underline{w} - \underline{X_n^H} d(n)\underline{w} - \underline{w}^H \underline{X_n} d^*(n)\right] = P_d + \underline{w}^H \underline{\underline{R}}\, \underline{w} - \underline{P}^H \underline{w} - \underline{w}^H \underline{P} \tag{4.3}$$

where $P_d = E[d(n)d^*(n)]$ is the power of the reference signal, $\underline{\underline{R}} = E\left[\underline{X_n}\underline{X_n^H}\right]$ the covariance matrix of the received snapshots and $\underline{P} = E\left[\underline{X_n} d^*(n)\right]$ the cross-correlation between snapshots and the reference signal.

Then, the gradient of the MSE with respect the conjugate of the desired beamvector is:

$$\nabla_{\underline{w}^H}\, \varepsilon = \underline{\underline{R}}\, \underline{w} - \underline{P} \tag{4.4}$$

This provides the optimal beamvector after equalising to zero the gradient:

$$\underline{w}_{opt} = \underline{\underline{R}}^{-1} \cdot \underline{P} \tag{4.5}$$

5. Channel Estimation & Equalization

5.1. Channel Estimation

The deployment of multiple antennas in the system can result in a significant capacity increase. This is due to two effects: diversity, i.e., robustness against fading of the channel between a transmitting and a receiver antenna, and space-time coding, i.e., the parallel transmission of information via multiple transmit antennas. In other chapters, however, this capacity increase was based on an important assumption: all channels between the transmitting and the receiver antennas are accurately known. In practice, these channels will have to be estimated, which is the focus of this section.

The wireless channel is highly complex. As it was commented for this study, it is both frequency- and time-selective, and with multiple antennas, also the space-selectivity plays a role. Although the channel modeling is simplified to a multipath propagation, there is an important trade off: a sophisticated model with more parameters may turn out to be less accurate when the parameters have to be estimated with a finite set of observations. This is the basis of channel estimation.

Channel estimation is based on non-blind and blind techniques. In practical systems, as LTE, channels are invariably estimated using periodic bursts of known reference symbols, therefore the thesis will focus on this non-blind technique, which only exploit the presence of the known reference signals presented in section 3.5.2.

Despite being an extensive topic, the thesis is limited on scaling the received error relative signal to the reference error by Weighting Factors to minimize the channel MSE. These factors are calculated from the Wiener's solution in Section 4.3, which finds the optimal in terms of the channel MSE.

When the estimation, based on the Wiener filter (weights) is performed on the transmitted symbol of the reference signal (pilot) noted as y_p, it is proposed the following schema as shown in Figure 5.1 where Wiener weights are directly multiplied with the pilot signal and then the resulting signal is passed to frequency domain resulting in the channel frequency estimation.

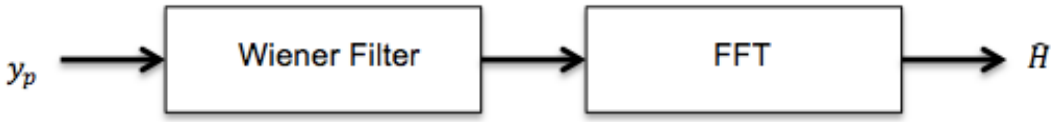


Figure 5.1 Channel Estimation on Pilots

5.2. Channel Equalization

As was mentioned, a multipath propagation results in ISI, which is far more destructive compared to channel and/or noise so that efforts are aimed at the goal of eliminating or at least mitigating the distortion caused by ISI. In this way, equalization has to be carried out for better demodulation.

Let E_m $(m = 0,1,2 \dots N-1)$ denote the equalizer coefficient for the *m*-th subcarrier and H_m the channel. The equalizer coefficients are determined to minimize the MSE between the equalized signal and the original signal. The equalizer coefficients are computed in two methods:

5.2.1. Zero-forcing (ZF) equalizer

The Zero Forcing (ZF) Equalizer is: $E_m = 1/H_m$ $(m = 0, 1, 2, \dots, N-1)$.

The coefficients are adjusted such that the equalizer output is forced to be zero. Then, possible interferences (such as ISI) are assumed to be zero. Even so, this results in noise amplification.

5.2.2. Minimum Mean Square Error (MMSE) equalizer

The Minimum Mean Square Error (MMSE) Equalizer is: $E_m = H_m^*/[|H_m|^2 + \left(\frac{Eb}{N_0}\right)^{-1}]$

The coefficients are adjusted such that the MSE of ISI and noise power at the equalizer output is minimized.

6. Simulations and results

6.1. Channel

The simulation tool in script *LTE_Channel.m* (See Appendix A.1) provides the possibility of choosing different channels taking into account a multipath fading propagation. There are presented three different channel models according to [5]: Extended Pedestrian A model (EPA), Extended Vehicular A model (EVA) and Extended Typical Urban model (ETU). These three delay profiles represent a low, medium and high delay spread environment respectively where low delay spreads are used to model indoor environments with small cell-sizes while medium and high delay spreads are used to model urban environments with large cells. For simplicity, Doppler is not considered.

In addition, these models are provided by a determined number of taps, which each of them corresponds to a multipath signal characterized by a fixed delay and relative average power. In order to obtain their channel impulse responses, the delays have to be divided by the sampling time Ts to obtain the position of the samples. The rest is zero-padded.

The normalized channel impulse and frequency responses are reflected on the following figures. The simulations are going to be based on a 5 MHz channel bandwidth, so they were designed for this operation. Then, simulation parameters are particularly taken from Table 3.1.

- EPA:

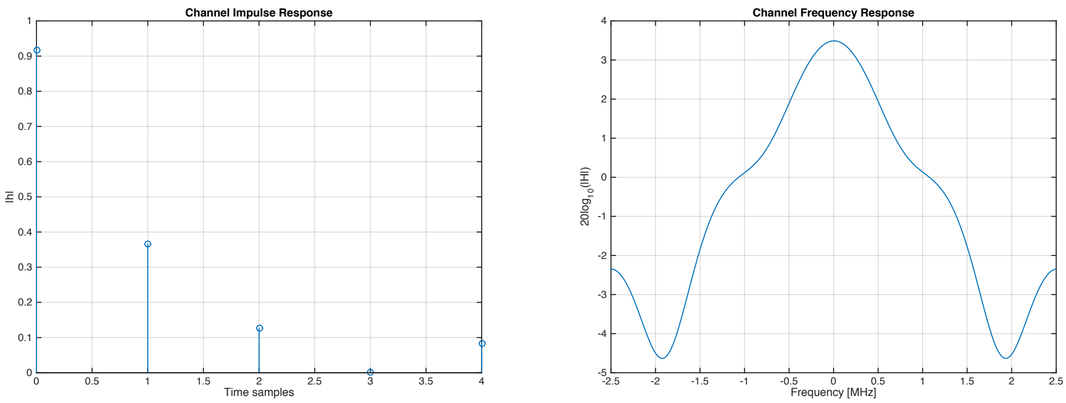


Figure 6.1 EPA Channel Impulse Response (left) and Frequency Response (right)

– EVA:

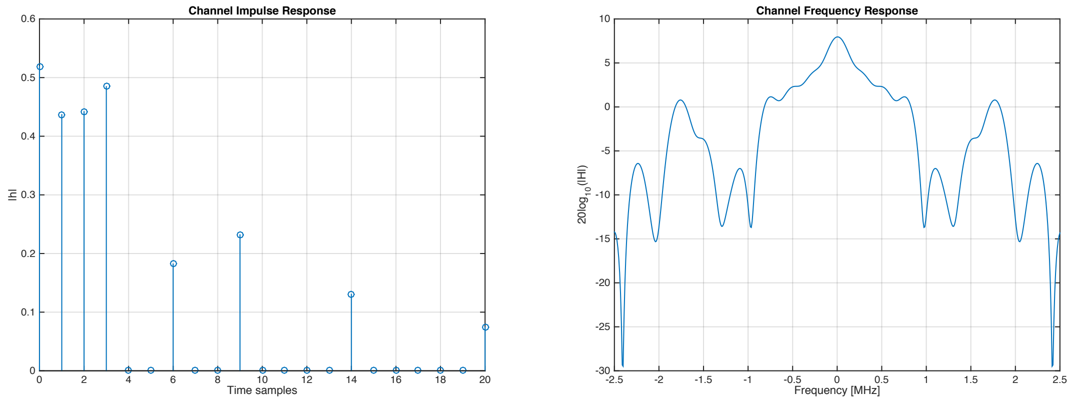


Figure 6.2 EVA Channel Impulse Response (left) and Frequency Response (right)

– ETU:

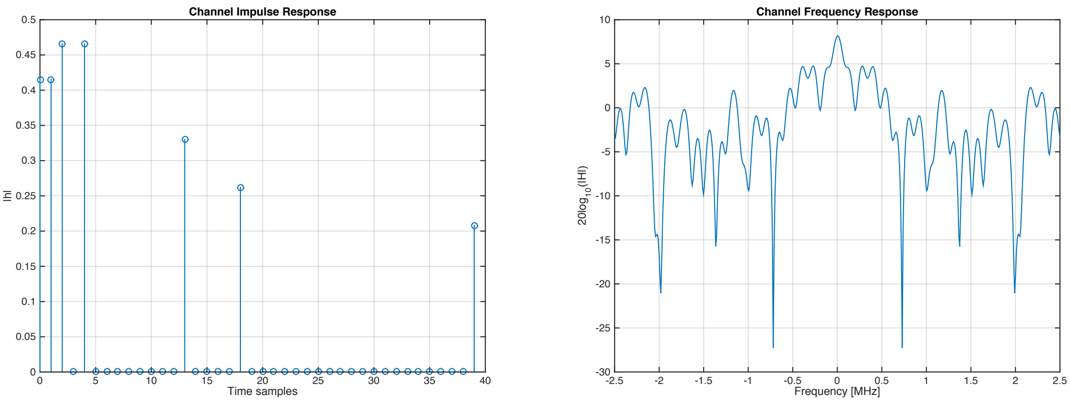


Figure 6.3 ETU Channel Impulse Response (left) and Frequency Response (right)

6.2. OFDM Background

This section is presented to give an overview of a multicarrier system operation and to fix different simulation parameters that are going to be used in the following sections of this chapter for the LTE uplink case.

The Matlab code that operates this simulation is the script *ofdm_system_full.m* (See Appendix A.2), which represents the implementation of a point-to-point OFDM system model as proved in Chapter 2. The final purpose is to plot the BER for different values of SNR using the Monte Carlo method (as the following sections), which consists in counting the number of error bits that differ between the input and output data stream bits, for then calculating the percentage that represents over the total transmitted bits. For simplicity, it is considered a transmitted power signal $P_s = 1$ in the scenario.

The parameters involved in the simulations are presented in the following table:

Table 6.1 Simulation parameters OFDM

Parameters	Value
Channel Bandwidth	5 MHz
FFT size	512
Cyclic Prefix Length (Extended)	128
Modulation type	QPSK (4QAM)
Number of iterations	1000
Channel Equalization	ZF/MMSE
Detection	Hard decision
Frequency Sampling	7.68 MHz

As it is seen in Table 6.1, the modulation type which will be simulated all the time is QPSK although the program allows to work with different M-QAM modulations as shown in Figure 6.4. This decision is to get better values of BER that are also achieved thanks to the application of a determined number of iterations.

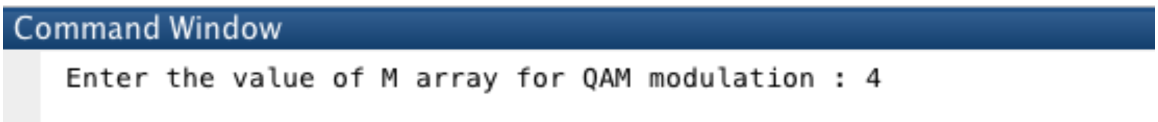


Figure 6.4 M-QAM Decision

First of all, let's take a look on the OFDM transmitted signal. The generation of the signal is given by a previous M-QAM modulator based on Gray Coding in order to improve BER from noise or any distortion so that close constellation points differ in few bits as possible. Assuming that, then it is given an OFDM modulation and the symbol after adding the CP is shown in Figure 6.5, where it can be observed the high Peak-to-Average Ratio (PAPR).

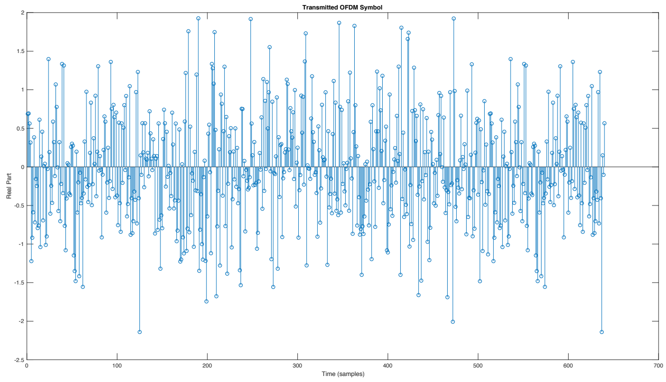


Figure 6.5 Transmitted OFDM Symbol Simulation

After passing through the channel, the received signal experiences the effect of multipath as it can be seen in the frequency domain. Figure 6.6 shows how the linear transmitted OFDM signal is clearly distorted by this effect, receiving worse values in some frequencies than others.

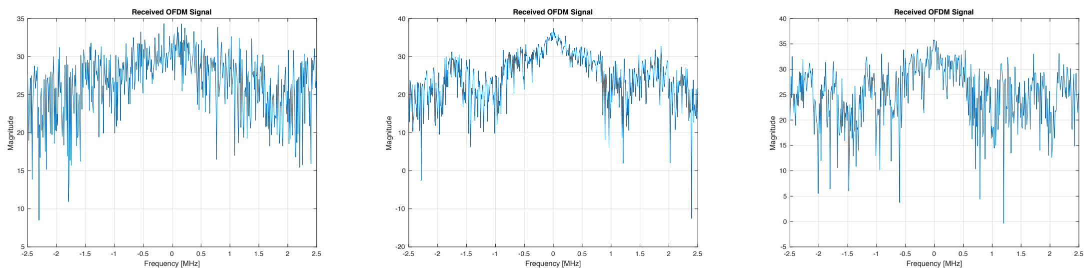


Figure 6.6 Received OFDM Signal after passing through EPA (left), EVA (centre), ETU (right) channel models with a SNR = 6 dB

On the other hand, the receiver does the inverse operation adding equalization and detection for coherent demodulation. The detection is fixed at a hard decision for simplicity, so it is assumed that is not decisive on the work for the simulation purposes.

On the contrary, equalization can be performed by the two methods presented in section 5.2: ZF and MMSE. After OFDM simulation, there are not appreciated significant differences between them. However, it is going to be proved afterwards if it has an impact on the uplink simulation.

In order to visualize the impact of the channel and the system, the results are given by the BER. Before proving the channels, the simulation tool gives the possibility to do a simulation without channel to prove if the system is working properly. The results have to represent the theoretical AWGN curve as shown in Figure 6.8.

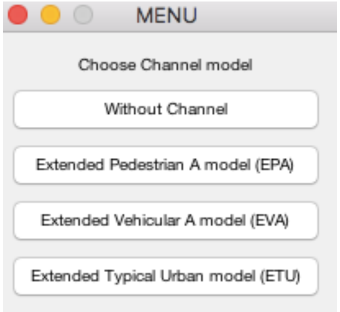


Figure 6.7 Channel Menu

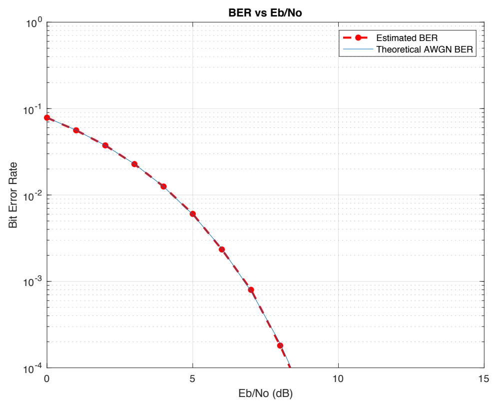


Figure 6.8 BER Without Channel

After this verification, the BER of an OFDM point-to-point communication is plotted with the different multipath channels proposed in Section 6.1 as follows. As it can be observed, there are also plotted theoretical AWGN and Rayleigh (fading) BER representations for analysing the behaviour of each channel in the system.

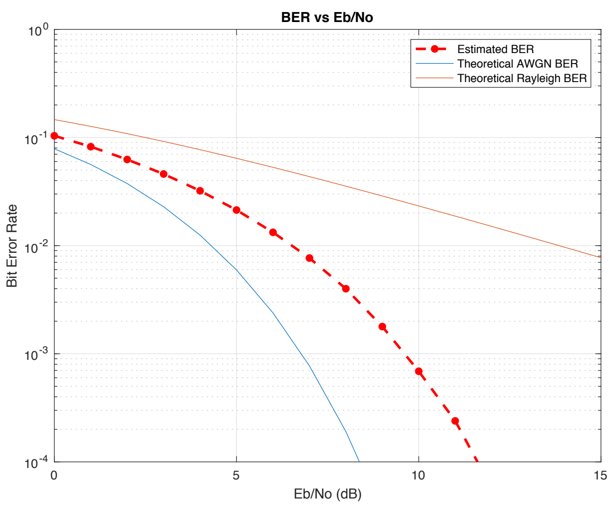


Figure 6.9 OFDM Simulation: BER with EPA channel with ZF Equalization

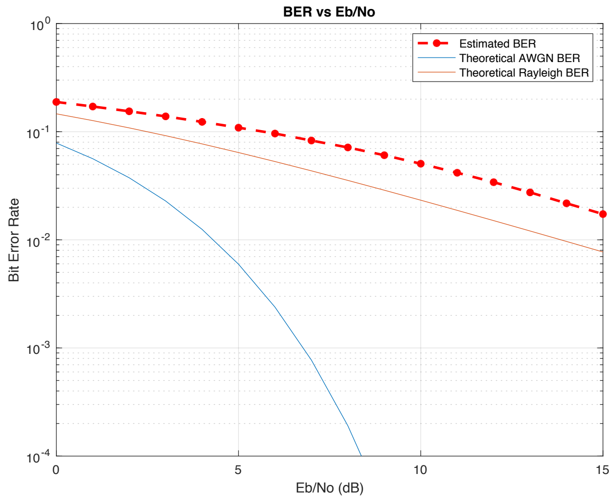


Figure 6.10 OFDM Simulation: BER with EVA channel with ZF Equalization

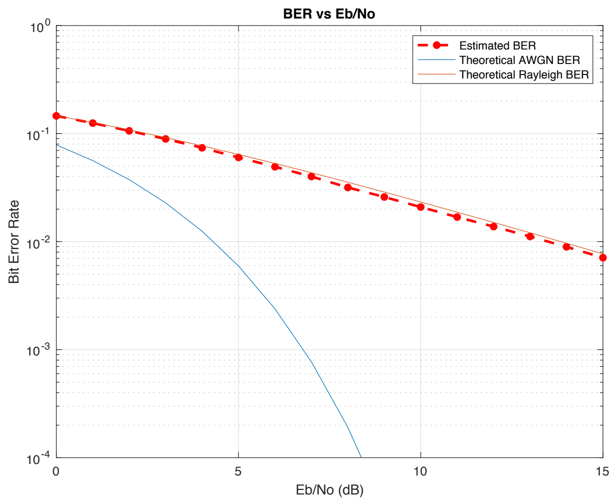


Figure 6.11 OFDM Simulation: BER with ETU channel with ZF Equalization

After simulation, it is observed the clear behaviour of the channels in the system. Despite EPA model achieves the best BER representation, it is far away to achieve a typical fading model compared to LTE practical situations due to its 'flat' behaviour as shown in Figure 6.1 and as a result, the BER representation is similar to the theoretical AWGN. On the other hand, EVA and ETU models have a similar behaviour, as they achieve frequency selectivity so that the BER is practical the theoretical fading representation. All in all, it is confirmed that the channel model that distorts less the signal is EPA (as it was observed in Figure 6.6). As it is considered multipath, simulations are going to be based on EVA and ETU channel models in the uplink to reflect this effect.

6.3. SC-FDMA Simulations

For SC-FDMA, part of the Matlab code structure is preserved as before adding the corresponding blocks and signals of the uplink access system presented in Chapter 3. The final purpose is to generate a program that simulates a point-to-point communication system for different users trying to access it, and see how the BER representation affects on each channel model and subcarrier mapping mode proposed.

First of all, let's consider a single user for determining the operation of each subcarrier mapping mode and the following simulation parameters:

Table 6.2 Simulation parameters SC-FDMA

Parameters	Value
Channel Bandwidth	5 MHz
FFT size	512
Total number of subcarriers	512
Cyclic Prefix Length (Extended)	128
Block of M QAM data symbols	16
Spreading Bandwidth (possible users)	4
Modulation type	QPSK (4QAM)
Number of iterations	1000
Channel Equalization	ZF/MMSE
Detection	Hard decision
Frequency Sampling	7.68 MHz
Subcarrier mapping	Interleaved/Localized

Before that, both equalization methods are compared in order to check which one is optimal in SC-FDMA. Results are shown by computing the BER for a localized mode and an ETU channel model.

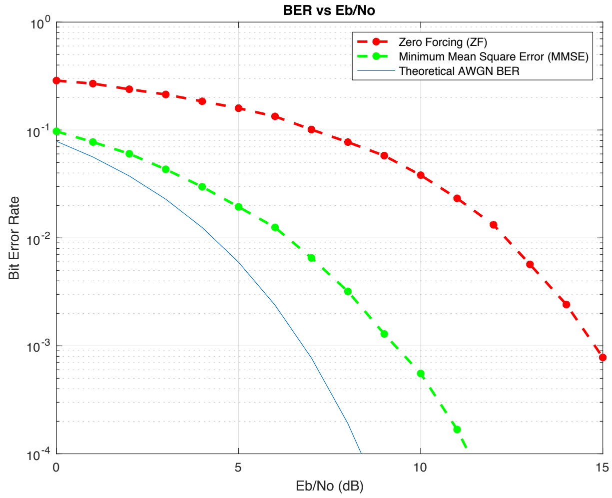


Figure 6.12 Performance of Channel Equalization

In this case, it can be noticed that the MMSE method is better than the ZF method, giving lower BER. Therefore, from now on, the MMSE method will be used in all simulations.

After system verification, the following BER results are presented for each channel model in order to compare the subcarrier mapping modes: Interleaved (Distributed) and Localized. The script *SCFDMA_Sucarrier_Mapping.m* (See Appendix A.3) manages it.

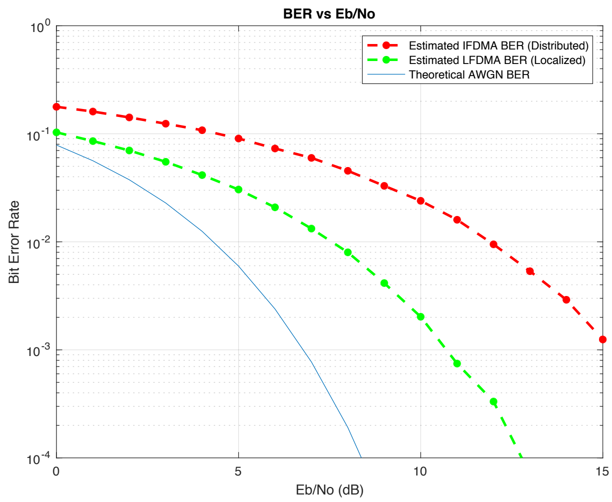


Figure 6.13 Subcarrier Mapping performance under EVA channel model with MMSE Equalization

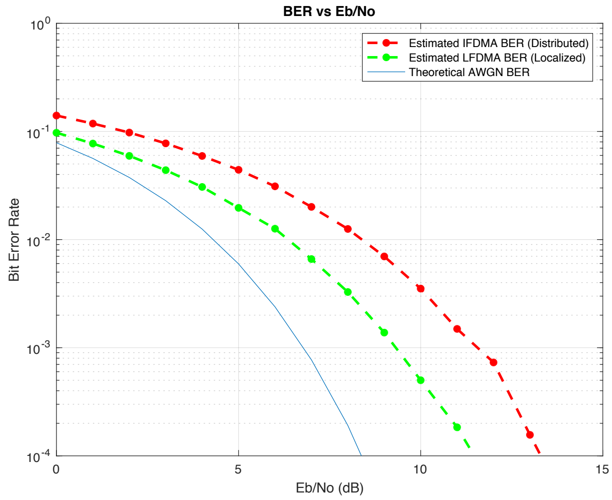


Figure 6.14 Subcarrier Mapping performance under ETU channel model with MMSE Equalization

Comparing both channels, it can be noticed that the system is run with better performance under the localized subcarrier mapping method. This makes sense, so it corresponds to the current implementation in LTE. Moreover, both EVA and ETU channel have similar results. As it is used a MMSE equalizer, the system is better performed for consecutive subcarriers so the mean error minimizes the subcarrier nulls along a consecutive fraction of subcarriers. Then, distributed mode is worse due to getting values from different positions without this linearity for avoiding nulls. For this uplink case, ETU channel achieves better performance in the system.

Next step is to simulate the system when there is more than one user connected to the base station. From now on, the simulations will be carried out for localized subcarrier mapping. For that, it is important to observe that signals will be consecutive constructed in frequency domain and then, demodulation will be given with this operation. This is shown in Figures 6.15 and 6.16 when two users are connected.

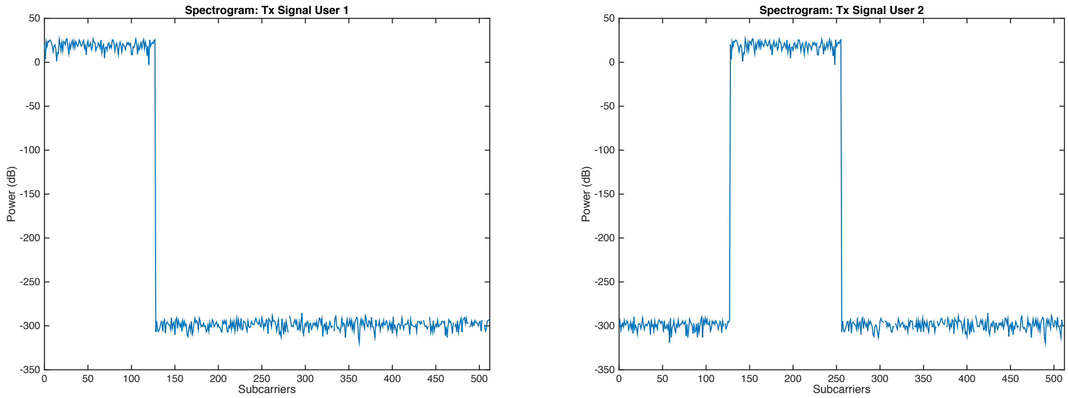


Figure 6.15 Transmitted Spectrogram for 2 users

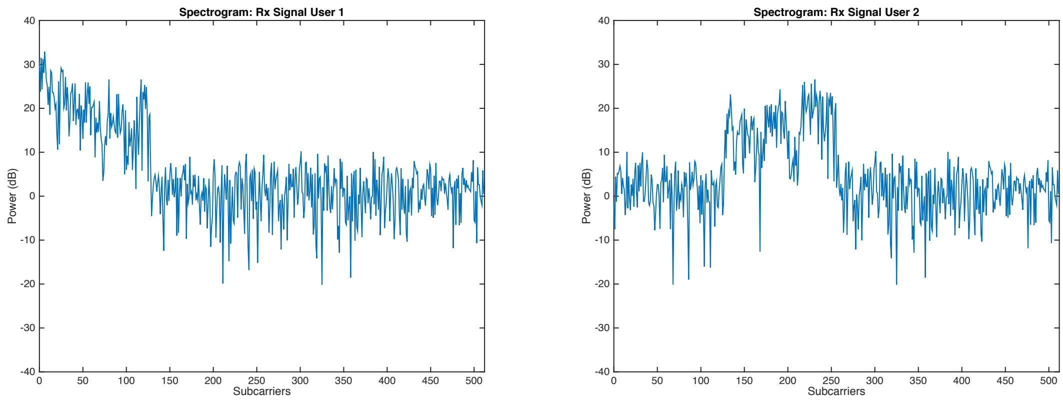


Figure 6.16 Received Spectrogram for 2 users (SNR = 18 dB and ETU channel model)

To see the impact of the channel for different users in the system, the script *SCFDMA_Multiple_Users.m* (See Appendix A.4) generates different signals for each user and represents their respective BER curve. Following the same example, EVA and ETU channel models are compared when all the four possible users are connected, as follows.

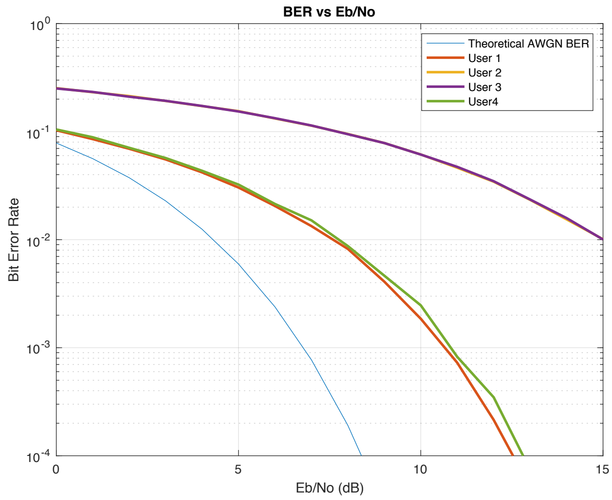


Figure 6.17 SC-FDMA 4 users performance under EVA channel model with MMSE Equalization

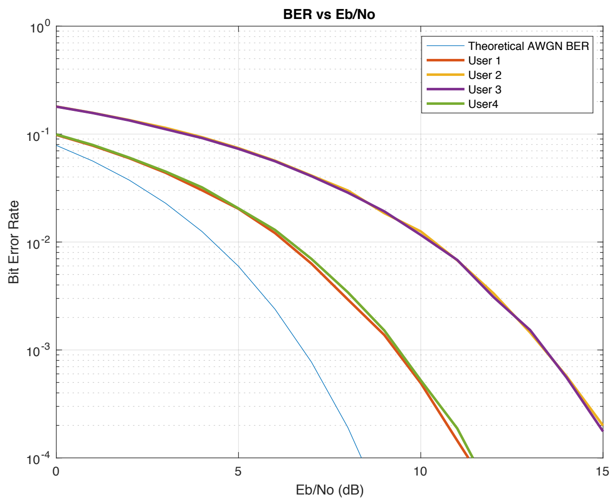


Figure 6.18 SC-FDMA 4 users performance under ETU channel model with MMSE Equalization

It can be noticed that users do not achieve the same BER as a result of subcarrier de-mapping and equalization, so they are directly dependant on the subcarrier spacing given by the occupied subcarriers within the channel. Therefore, users 1 and 4, and users 2 and 3 have the same BER because they are affected by the same periodic part of the channel. Moreover, MMSE equalization plays the role of taking into account the noise level and hence each user in his corresponding frequency domain has a different quality.

On the contrary, let's consider working with ZF equalization.

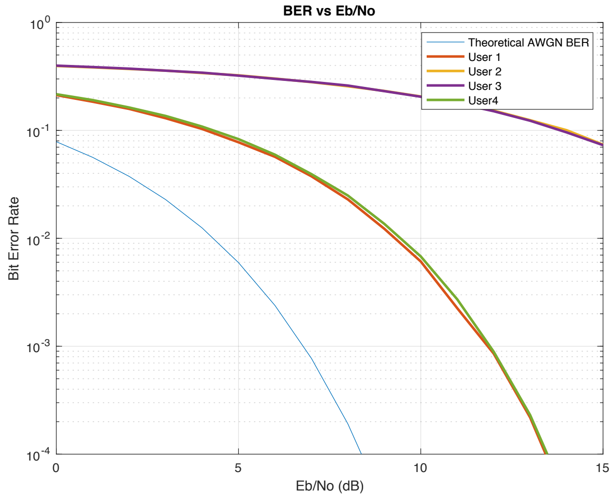


Figure 6.19 SC-FDMA 4 users performance under EVA model channel with ZF Equalization

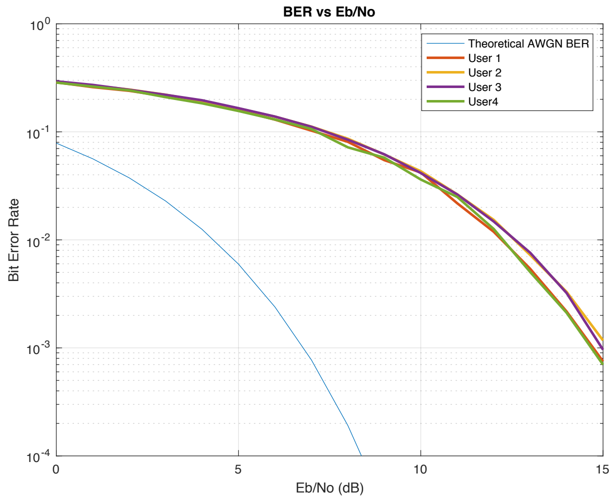


Figure 6.20 SC-FDMA 4 users performance under ETU channel model with ZF Equalization

In this case, it can be noted that ZF Equalization causes system performance degradation when there exist deep nulls in the channel's frequency response. As it can be seen in the case of ETU, even the performance may result in giving the same quality between users as the frequency nulls affect in the same way on each subcarrier spacing.

All in all, it will be followed the example of MMSE for applying an adaptive beamformer as follows.

6.4. Adaptive Beamforming

To simulate this section, it is going to consider the following example as shown in Figure 6.21, which is defined in *Beamforming.m* (See Appendix A.5): 4 users transmitting with the same power and at certain elevation angles, and a linear antenna array design formed by 16 receiving antennas, which are separated 0.5λ, at the base station.

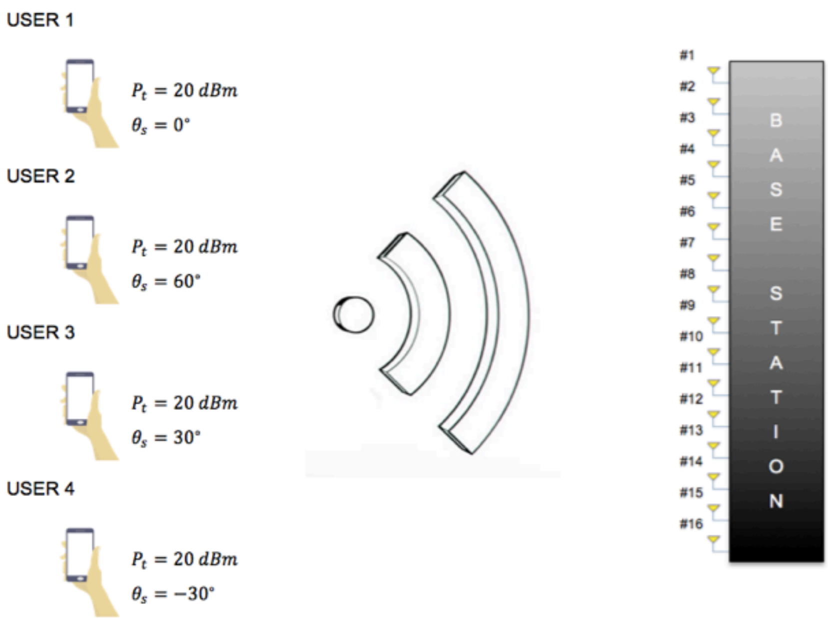


Figure 6.21 Beamforming simulation

In order to obtain the beamforming of the scenario, reference signals have to be taken into account. The objective is to send a subframe to the base station for calculating the covariance matrix of the received snapshots, allocating the corresponding reference symbols as shown in Figure 3.9. As it is considered a 5 MHz bandwidth, the number of snapshots is 7680, which will be the computing average to calculate the corresponding Mathematical Expectation $E[\dots]$ of $\underline{\underline{R}}$ and $\underline{P}$ for obtaining the Wiener weights.

The script that does this operation is *RS_Uplink.m* (See Appendix A.8), which calls to the corresponding main script of the CTTC software to compute $\underline{\underline{R}}$, adapting the corresponding simulation values and passing the corresponding subframe signal as source waveforms.

First of all, the program calls the function *ZadoffChuSeq.m* (See Appendix A.6), which generates the Zadoff-Chu cyclically extended sequence of length $N_p = 12 * 25 = 300$ with $N_{zc} = 293$ and $q = 25$. Then, from it, the signal is passed to time domain as shown in Figure 6.22.

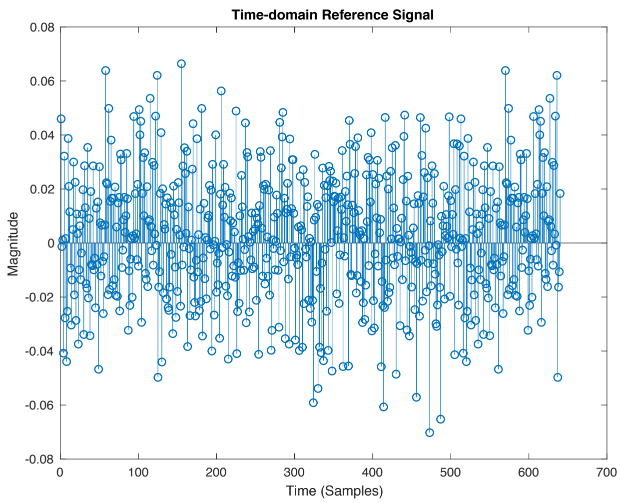


Figure 6.22 Time-domain Reference Signal

Then, the subframe is created by calling the script *SCFDMA_Subframe.m* (See Appendix A.7), adding the reference symbol in the 3rd position of the slot as shown in time-domain for each user in Figure 6.23.

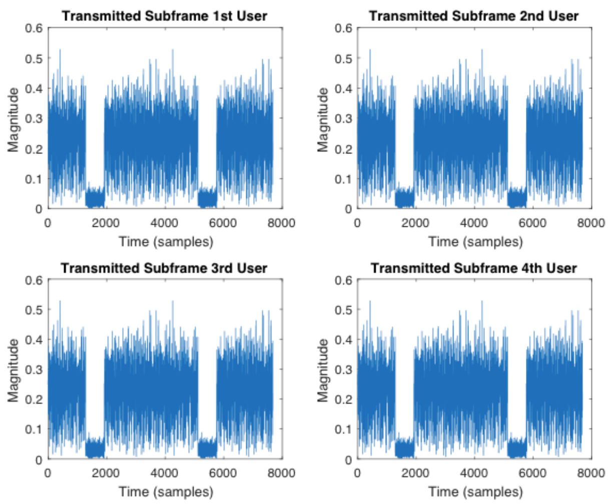


Figure 6.23 Transmitted Subframe

After sending the subframe, the program generates snapshots and computes covariance by averaging all the snapshots. In addition, each snapshot is saved in a matrix that will be used to calculate $\underline{P}$ in the same way than $\underline{\underline{R}}$.

Once is calculated, the beamforming is checked by plotting the array factor as described in *pattern.m* (See Appendix A.9). The simulation is based on pointing to a specific user and then, cancelling the interferences coming from the other users.

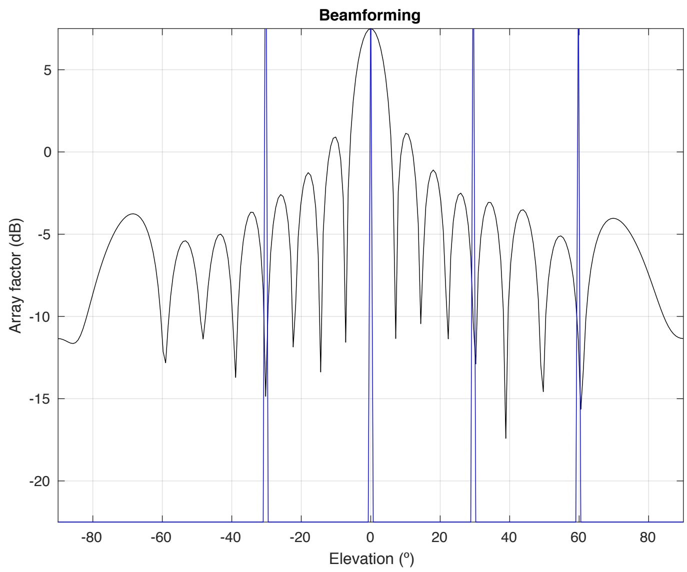


Figure 6.24 Beamforming User 1

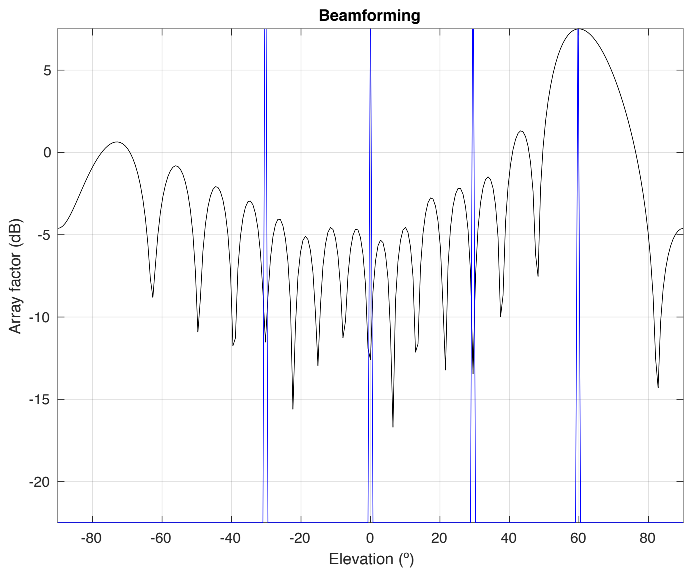


Figure 6.25 Beamforming User 2

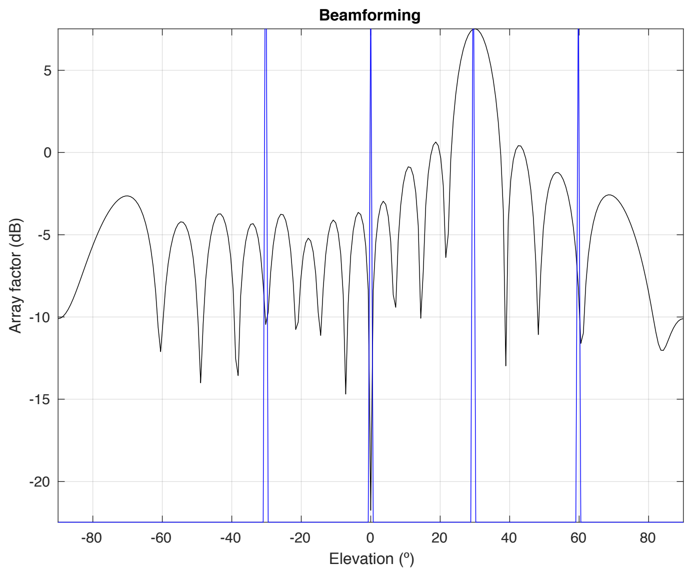


Figure 6.26 Beamforming User 3

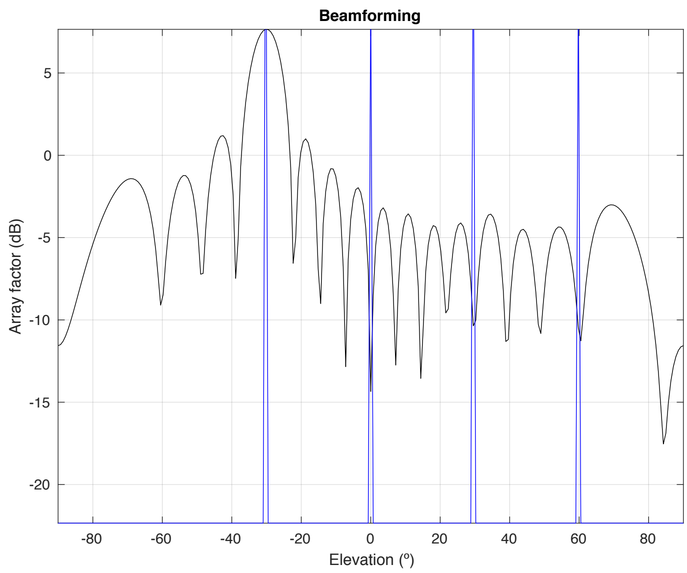


Figure 6.27 Beamforming User 4

Indeed, it is observed that when it is pointed to a specific user, this achieves maximum gain while the other ones are cancelled by tending to zero. These results correspond to the beamformer operation.

Next step is to calculate Wiener weights. Before that, the time-domain reference signal has to be divided in four parts following SDMA criterion. Then, each user will have particular Wiener weights as shown in the following figure.

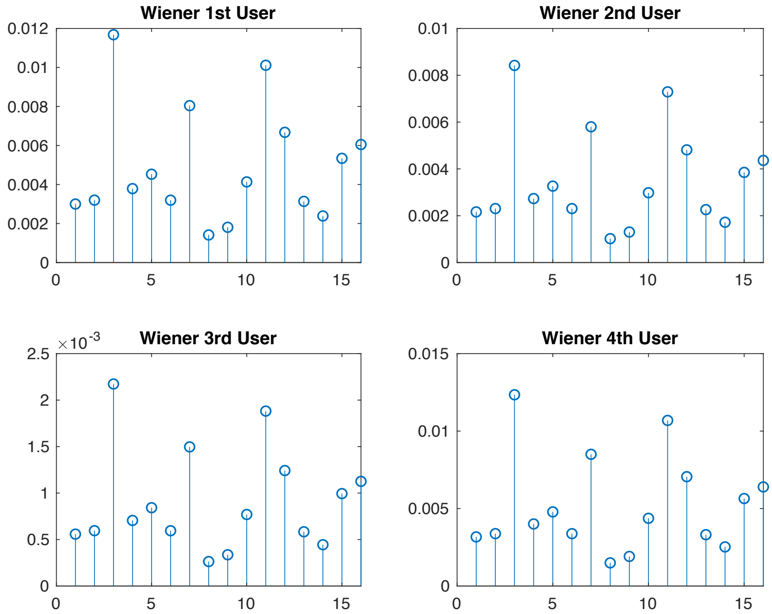


Figure 6.28 Wiener weights of each user

Finally, channel estimation is operated by the function *Channel_Estimation.m* (See Appendix A.10) following the proposed schema in chapter 4. The new main operation is given by script *SCFDMA_TRB.m* (See Appendix A.11) to represent the corresponding BER following the same Matlab code as SCFDMA simulations, but in this case the reference signal is loaded and the received reference symbol is passed to the channel estimation function. Then, the demodulation process gives to the result shown in Figure 6.29.

As final simulation, it is represented the BER when the system applies the whole smart operation: the beamformer plus channel estimation.

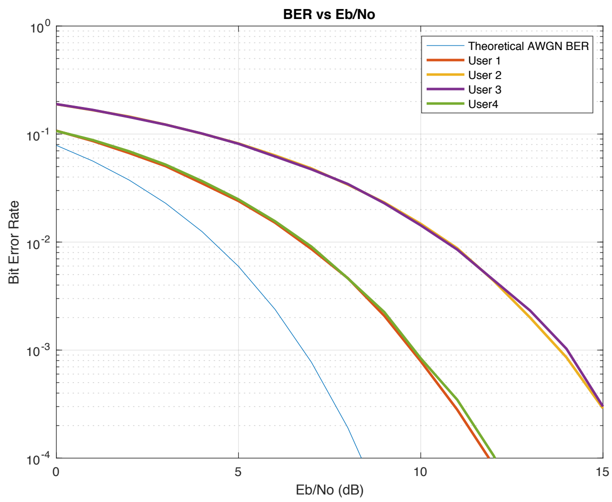


Figure 6.29 TRB Performance under ETU channel model with Beamformer and Channel Estimation

Comparing with Figure 6.18, the system clearly maintains the same operation between users. Then, it is confirmed that the system operates in the same way without the necessity of knowing the channel, which incurs in the cancellation of interferences when all users are transmitting at the same time. Then, quality between users is preserved taking into account the importance of the subcarrier bandwidth that they occupy in the transmission.

7. Budget

In this chapter, there is presented the corresponding economy impact of the project. The total cost corresponds basically to the dedicated hours for all the studies involved in it, assuming a role of a junior engineer with a cost of 8 €/hour.

Moreover, it is reflected the cost of the Matlab software that was needed to present the results. Although the license number is not provided, the cost is assumed to be for a basic student download package during a year.

The detailed evaluated cost is presented in the following table:

Table 7.1 Total project cost

ENGINEERING HOURS

Investigation	Hours	Cost
OFDM Signal Generation	25 h	200.00 €
OFDM Communication System	60 h	480.00 €
SUBTOTAL OFDM	*85 h*	*680.00 €*
SC-FDMA Signal Generation	15 h	120.00 €
SC-FDMA Subcarrier Mapping	175 h	1,400.00 €
SC-FDMA Reference Signals	35 h	280.00 €
SC-FDMA SDMA	35 h	280.00 €
SUBTOTAL SC-FDMA	*260 h*	*2,080.00 €*
SC-FDMA Beamforming	175 h	1,400.00 €
SC-FDMA Channel Estimation	70 h	560.00 €
SUBTOTAL BEAMFORMING	*245 h*	*1,960.00 €*
SOFTWARE		
MATLAB_R2018a	-	35.00 €
TOTAL	**590 h**	**4,755.00 €**

8. Conclusions and future lines

The simulations, which are carried out in the project, have been able to confirm good part of the multiple access technique principles applied on the physical layer in uplink LTE, characterizing the performance through illustrations and results.

In particular, the optimal result has been applied by comparing and increasing the complexity in the system, in order to demonstrate the smart system operation for Uplink LTE. For that reason, it has been plotted BER representations to give an overview of the quality of the system.

First was proved that the localized subcarrier mapping method was the suitable one to work with in uplink LTE having an important impact on the quality of each user in relation to the subcarrier spacing within the channel. On the other hand, the method applied for channel equalization varied dependent on user's quality and channel characteristics.

In addition, adaptive beamforming is a good way to null multiple interfering signals, as it was seen on the radiation pattern of the antenna array, and also provide good quality to the users. Even so, there is a high dependant relation in the way that the channel has to be estimated at the receiver to achieve a practical situation when the channel is supposed not to be known.

But, on the other hand, as the multipath propagation is presented, the system can't be able to ensure the optimal operation of the communication for the entire number of users. Then, the important key that comes to the fore is the adjustment of this addition in the system, exploiting the increased knowledge of the spatial channel characteristics. Then, further studies can be performed to explore adaptive solutions that minimize the effect of multipath. For that, it is proposed to follow this line by simulating a MDIR receiver, which applies a specific channel depending on the path that is received.

All in all, practical situations have added values to deal with as the project validates. Even this complexity is higher in reality, so each signal arrives to each sensor with a particular delay group, which may destroy the orthogonality of the subcarriers. Then, design has to be always readjusted to perform the best practical operation of the system.

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Appendix A: MATLAB Code

A.1. LTE_Channel.m

```
%*********************************************************************
%                          LTE_Channel
%*********************************************************************
%   PROJECT: OFDM Smart Beamforming
%   Author: Paul Otterstein Bolos
%
%   Operation:    Generates LTE Channels (EPA, EVA, ETU) and displays a
%                 Menu to choose them
%
%---------------------------------------------------------------------

% Without Channel - This is identity channel for AWGN simulation
idenChannel = 1;

% Extended Pedestrian A model (EPA)
pathDelays_EPA = ceil([0 30 70 90 110 190 410]*1e-9./Ts);
avgPathGains_EPA = [0 -1 -2 -3 -8 -17.2 -20.8];
avgPathGains_linear_EPA = 10.^(avgPathGains_EPA/20);
Lch_EPA = pathDelays_EPA(end)+1;
EPAchannel = zeros(1,Lch_EPA);
EPAchannel(pathDelays_EPA+1) = avgPathGains_linear_EPA;
% Normalize the channel
EPAchannel = EPAchannel/sqrt(sum(EPAchannel.^2));

% Extended Vehicular A model (EVA)
pathDelays_EVA = ceil([0 30 150 310 370 710 1090 1730 2510]*1e-9./Ts);
avgPathGains_EVA = [0 -1.5 -1.4 -3.6 -0.6 -9.1 -7 -12 -16.9];
avgPathGains_linear_EVA = 10.^(avgPathGains_EVA/20);
Lch_EVA = pathDelays_EVA(end)+1;
EVAchannel = zeros(1,Lch_EVA);
EVAchannel(pathDelays_EVA+1) = avgPathGains_linear_EVA;
% Normalize the channel
EVAchannel = EVAchannel/sqrt(sum(EVAchannel.^2));

% Extended Typical Urban model (ETU)
pathDelays_ETU = ceil([0 50 120 200 230 500 1600 2300 5000]*1e-9./Ts);
avgPathGains_ETU = [-1 -1 -1 0 0 0 -3 -5 -7];
avgPathGains_linear_ETU = 10.^(avgPathGains_ETU/20);
Lch_ETU = pathDelays_ETU(end)+1;
ETUchannel = zeros(1,Lch_ETU);
ETUchannel(pathDelays_ETU+1) = avgPathGains_linear_ETU;
% Normalize the channel
ETUchannel = ETUchannel/sqrt(sum(ETUchannel.^2));
```

```
% Channel model choice
choice = menu('Choose Channel model','Without Channel','Extended
Pedestrian A model (EPA)','Extended Vehicular A model (EVA)','Extended
Typical Urban model (ETU)');
switch choice
    case 1
        h = idenChannel;
        nn = 0;
    case 2
        h = EPAchannel;
        nn = 0:Lch_EPA-1;
    case 3
        h = EVAchannel;
        nn = 0:Lch_EVA-1;
    case 4
        h = ETUchannel;
        nn = 0:Lch_ETU-1;
end

H = fft(h,Nfft);
H_shift = fftshift(H);

% Uncomment to represent Channel Impulse and Frequency Responses
% if choice == 2 || choice == 3 || choice == 4
%     % Channel Impulse Response
%     figure(1)
%     stem(nn,abs(h))
%     xlabel('Time samples');
%     ylabel('|h|');
%     title('Channel Impulse Response');
%     grid on;
%
%     % Frequency domain version of the channel response
%     figure(2)
%     f = linspace(-BW/2,BW/2,Nfft);
%     plot(f,10*log10(H_shift.*conj(H_shift)));
%     xlabel('Frequency [MHz]');
%     ylabel('20log_1_0(|H|)');
%     title('Channel Frequency Response');
%     grid on;
%
% end
```

A.2. ofdm_system_full.m

```
%************************************************************************
%                              ofdm_system_full
%************************************************************************
%   PROJECT: OFDM Smart Beamforming
%   Author: Paul Otterstein Bolos
%
%   Operation:
%
%   1- OFDM Transmitter
%
%   ***Channel Choice*** (+ Noise)
%
%   2 - OFDM Receiver
%
%   ***BER Calculation from the input/output data system***
%
%------------------------------------------------------------------------

clc;
close all;

%%%%%%%%%%%%%%%%%%%%%%%%%%%% PARAMETERS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Channel Bandwidth (in MHz)
BW = 5;
% Generation of M-QAM modulation - Size of signal constellation
M = input(' Enter the value of M array for QAM modulation : ');
% Number of bits per symbol
k = log2(M);
% FFT size (symbol size without CP)
Nfft = 512;
% Cyclic Prefix Length (Extended CP)
Ncp = 128;
% Number of bits to process
numBits = k*Nfft;
% Sampling frequency
fs = 7.68e6;
% Sampling Time
Ts = 1/fs;
% Number of simulation iterations
numIterations = 1000;
% Eb/No Vector (from 0 to 15 dB)
EbNoVec = (0:15)';
% Convert Eb/No to SNR in dB (SNR = Eb/No * k)
snrdB = EbNoVec + 10*log10(k);

%%%%%%%%%%%%%%%%%%%%%%%%%%%% CHANNEL %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

LTE_Channel;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% Results for every EbNo <-> SNR (BER SIMULATION)
for n = 1:length(snrdB)
    tic;
    % Initialize the error count
    numerrs = 0;

    % Results for every iteration
    for m = 1:numIterations


        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %                      1. TRANSMITTER
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


        %%%%%%%%%%%%%%%%%%%%%% INPUT DATA %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        % Incoming Bit Stream
        dataIn = randi([0 1], 1, numBits);

        % Serial to Parallel Converter
        dataInMatrix = reshape(dataIn, k, length(dataIn)/k).';

        % Bit to Constellation Mapping
        % Convert to integers (integer vector)
        dataSymbolsIn = bi2de(dataInMatrix,'left-msb').';
        % norms for BPSK 4-QAM 16-QAM...
        norms = [1 sqrt(2) 0 sqrt(10) 0 sqrt(42)];
        % Modulated source symbols (Gray Coding normalized)
        SymbolsIn = qammod(dataSymbolsIn,M,'gray')/norms(k);

        %%%%%%%%%%%%%%%%%%%%%%%%% IFFT %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        TxSamples = sqrt(Nfft)*ifft(SymbolsIn);

        %%%%%%%%%%%%%%%%%%%% ADD CYCLIC PREFIX %%%%%%%%%%%%%%%%%%%%%%%%%

        ofdmSymbol = [TxSamples(Nfft-Ncp+1:Nfft) TxSamples];


        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %                        CHANNEL + AWGN
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


        %%%%%%%%%%%%%%%%%%%% CHANNEL PROPAGATION %%%%%%%%%%%%%%%%%%%%%%%

        RxSamples = filter(h, 1, ofdmSymbol);        % Multipath Channel

        %%%%%%%%%%%%%%%%%%%%%%% AWGN NOISE %%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        % Generate AWGN with appropiate noise power
        tmp = randn(2, Nfft+Ncp);
        complexNoise = (tmp(1,:) + 1i*tmp(2,:))/sqrt(2);
        noisePower = 10^(-snrdB(n)/10);

        % Add AWGN to the transmitted signal
        RxSamples = RxSamples + sqrt(noisePower)*complexNoise;
```

```
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %                         2. RECEIVER
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


        %%%%%%%%%%%%%%%%%%%%% REMOVE CYCLIC PREFIX %%%%%%%%%%%%%%%%%%%%%

        EstSymbols = RxSamples(Ncp+1:Nfft+Ncp);

        %%%%%%%%%%%%%%%%%%%%%%% N-POINT FFT %%%%%%%%%%%%%%%%%%%%%%%%%%%%

        % Convert the received signal into frequency domain
        Y = fft(EstSymbols, Nfft);

        %%%%%%%%%%%%%%%%%%%%% EQUALIZATION %%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        % Zero Forcing (ZF)
        Y_ZF = Y./H;

        % Minimum Mean Square Error (MMSE)
        E = conj(H)./(conj(H).*H + 10^(-snrdB(n)/10));
        Y_MMSE = Y.*E;

        %%%%%%%%%%%%%%%%%%%%% OUTPUT DATA %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        % Hard decision detection
        %dataOutput = qamdemod(Y_ZF*norms(k),M,'gray','OutputType','bit',
         'UnitAveragePower',true).';
        dataOutput=qamdemod(Y_MMSE*norms(k),M,'gray','OutputType','bit',
        'UnitAveragePower',true).';

        % Finds the nº of bits that differ between the Input and Output
          bits Matrix
        % Count errors:
        numerrs = numerrs + biterr(dataInMatrix,dataOutput,k);

    end

    %%%%%%%%%%%%%%%%%%%%%%% BER CALCULATION %%%%%%%%%%%%%%%%%%%%%%%%%%%%

    BER(n) = numerrs/(numBits*numIterations);
    [snrdB(n) BER(n)]
    toc
end

% Transmitted OFDM Symbol Plot
figure(3)
stem(real(ofdmSymbol))
xlabel('Time (samples)')
ylabel('Real Part')
title('Transmitted OFDM Symbol')
```

```
% Plotting BER vs Eb/No
figure(5)
% Plot AWGN Theoretical Curve
ber_awgnTheory = berawgn(EbNoVec,'qam',M);
% Plot Rayleigh Theoretical Curve diversity order 1
ber_rayleighTheory = berfading(EbNoVec,'qam',M,1);
% Plot Estimated Curve
semilogy(EbNoVec,BER,'--*r','linewidth',2)
hold on
semilogy(EbNoVec,ber_awgnTheory)
hold on
semilogy(EbNoVec,ber_rayleighTheory)
axis([0 15 10^-4 1])
grid
legend('Estimated BER','Theoretical AWGN BER','Theoretical Rayleigh
BER')
xlabel('Eb/No (dB)')
ylabel('Bit Error Rate')
title('BER vs Eb/No')
```

A.3. SCFDMA_Subcarrier_Mapping.m

```
%*************************************************************************
%                        SCFDMA_Subcarrier_Mapping
%*************************************************************************
%
%   PROJECT: OFDM Smart Beamforming
%   Author: Paul Otterstein Bolos
%
%   Operation: SC-FDMA point-to-point Simulation:
%               -   Signal Generation and BER simulation
%               -   1 User
%               -   Subcarrier Mapping comparison
%
%-------------------------------------------------------------------------
clc;
close all;

%%%%%%%%%%%%%%%%%%%%%%%%%%% PARAMETERS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Channel Bandwidth (in MHz)
BW = 5;
% FFT size
Nfft = 512;
% Cyclic Prefix Length (Extended CP)
Ncp = 128;
% Total number of subcarriers
N = Nfft;
% Block of M QAM data symbols (data block size)
M = 128;
% Bandwidth Spreading Factor
Q = N/M;
% Size of QAM signal constellation
QAM = input(' Enter the value of M array for QAM modulation : ');
% Number of bits per symbol
m = log2(QAM);
% Number of bits to process
numBits = m*M;
```

```
% Eb/No Vector (from 0 to 15 dB)
EbNoVec = (0:15)';
% Convert Eb/No to SNR in dB (SNR = Eb/No * m)
snrdB = EbNoVec + 10*log10(m);
% Number of simulation iterations
numIterations = 1000;
% Sampling Frequency
fs = 2*3.84e6;
% Sampling Time
Ts = 1/fs;

%%%%%%%%%%%%%%%%%%%%%%%%%%% CHANNEL %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

LTE_Channel;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


% Results for every EbNo <-> SNR (BER SIMULATION)
for n = 1:length(snrdB)
    tic;
    % Initialize the error count
    numerrs_IFDMA = 0;
    numerrs_LFDMA = 0;

    % Results for every iteration
    for k = 1:numIterations


        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
        %                         TRANSMITTER
        %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


        %%%%%%%%%%%%%%%%%%%%%% INPUT DATA %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        % Incoming Bit Stream
        dataIn = randi([0 1], 1, numBits);

        % Serial to Parallel Converter
        % Reshape data into binary m-tuples
        dataInMatrix = reshape(dataIn, m, length(dataIn)/m).';

        % Bit to Constellation Mapping
        % Convert to integers (integer vector)
        dataSymbolsIn = bi2de(dataInMatrix,'left-msb').';
        % norms for BPSK 4-QAM 16-QAM...
        norms = [1 sqrt(2) 0 sqrt(10) 0 sqrt(42)];
        % Modulated source symbols (Gray Coding normalized)
        SymbolsIn = qammod(dataSymbolsIn,QAM,'gray')/norms(m);

        %%%%%%%%%%%%%%%%%% M-POINT DFT SPREADING %%%%%%%%%%%%%%%%%%%%%%%

        SymbolsIn_freq = fft(SymbolsIn);
```

```
%%%%%%%%%%%%%%%%%%%% SUBCARRIER MAPPING %%%%%%%%%%%%%%%%%%%%%%%%

% Interleaved (Distributed)
SamplesIn_IFDMA = zeros(1,N);
SamplesIn_IFDMA(1:Q:N) = SymbolsIn_freq;

% Localized
SamplesIn_LFDMA = zeros(1,N);
SamplesIn_LFDMA(1:M) = SymbolsIn_freq;

%%%%%%%%%%%%%%%%%%%%%% N-POINT IFFT %%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Convert the signal back to time domain
SamplesIn_IFDMA = ifft(SamplesIn_IFDMA);
SamplesIn_LFDMA = ifft(SamplesIn_LFDMA);

%%%%%%%%%%%%%%%%%%%% ADD CYCLIC PREFIX %%%%%%%%%%%%%%%%%%%%%%%%%

TxSamples_IFDMA = [SamplesIn_IFDMA(N-Ncp+1:N) SamplesIn_IFDMA];
TxSamples_LFDMA = [SamplesIn_LFDMA(N-Ncp+1:N) SamplesIn_LFDMA];

if k == 1
    % Compute and plot Tx spectrogram
    [y_IFDMA,freq_IFDMA,samples_IFDMA,p_IFDMA] =
    spectrogram(TxSamples_IFDMA, Nfft, 0, Nfft, fs);
    [y_LFDMA,freq_LFDMA,samples_LFDMA,p_LFDMA] =
    spectrogram(TxSamples_LFDMA, Nfft, 0, Nfft, fs);

    % Re-arrange frequency axis and spectrogram to put zero
    frequency in the middle of the axis
    freq_IFDMA = (freq_IFDMA-fs/2)/1e6;
    freq_LFDMA = (freq_LFDMA-fs/2)/1e6;
    p_IFDMA = fftshift(10*log10(abs(p_IFDMA)));
    p_LFDMA = fftshift(10*log10(abs(p_LFDMA)));

    figure(3)
    plot(freq_IFDMA,p_IFDMA);
    xlabel('Frequency (MHz)');
    ylabel('Power (dB)');
    title('Spectrogram: Tx Signal (IFDMA)');

    figure(4)
    plot(freq_LFDMA,p_LFDMA);
    xlabel('Frequency (MHz)');
    ylabel('Power (dB)');
    title('Spectrogram: Tx Signal (LFDMA)');
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                        CHANNEL + AWGN
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%% CHANNEL PROPAGATION %%%%%%%%%%%%%%%%%%%%%%%

% Multipath Channel
RxSamples_IFDMA = filter(h, 1, TxSamples_IFDMA);
RxSamples_LFDMA = filter(h, 1, TxSamples_LFDMA);
```

```
%%%%%%%%%%%%%%%%%%%%%%% AWGN NOISE %%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tmp = randn(2, N+Ncp);
complexNoise = (tmp(1,:) + 1i*tmp(2,:))/sqrt(2);
% Signal Power Transmitted
Ps = 1;
noisePower = Ps*10^(-snrdB(n)/10);
RxSamples_IFDMA = RxSamples_IFDMA +
sqrt(noisePower/Q)*complexNoise;
RxSamples_LFDMA = RxSamples_LFDMA +
sqrt(noisePower/Q)*complexNoise;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                            RECEIVER
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 if k == 1
    % Compute and plot Rx spectrogram
    [y_IFDMA,freq_IFDMA,samples_IFDMA,p_IFDMA] =
    spectrogram(RxSamples_IFDMA, Nfft, 0, Nfft, fs);
    [y_LFDMA,freq_LFDMA,samples_LFDMA,p_LFDMA] =
    spectrogram(RxSamples_LFDMA, Nfft, 0, Nfft, fs);

    % Re-arrange frequency axis and spectrogram to put zero
    frequency in the middle of the axis
    freq_IFDMA = (freq_IFDMA-fs/2)/1e6;
    freq_LFDMA = (freq_LFDMA-fs/2)/1e6;
    p_IFDMA = fftshift(10*log10(abs(p_IFDMA)));
    p_LFDMA = fftshift(10*log10(abs(p_LFDMA)));

    figure(5)
    plot(freq_IFDMA,p_IFDMA);
    xlabel('Frequency (MHz)');
    ylabel('Power (dB)');
    title('Spectrogram: Rx Signal (IFDMA)');

    figure(6)
    plot(freq_LFDMA,p_LFDMA);
    xlabel('Frequency (MHz)');
    ylabel('Power (dB)');
    title('Spectrogram: Rx Signal (LFDMA)');
end

%%%%%%%%%%%%%%%%%%%%% REMOVE CYCLIC PREFIX %%%%%%%%%%%%%%%%%%%%

RxSamples_IFDMA = RxSamples_IFDMA(Ncp+1:N+Ncp);
RxSamples_LFDMA = RxSamples_LFDMA(Ncp+1:N+Ncp);

%%%%%%%%%%%%%%%%%%%%%%% N-POINT FFT %%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Convert the received signal into frequency domain
Y_IFDMA = fft(RxSamples_IFDMA, Nfft);
Y_LFDMA = fft(RxSamples_LFDMA, Nfft);
```

```
        %%%%%%%%%%% SUBCARRIER DEMAPPING + EQUALIZATION (ZF) %%%%%%%%%%%

        % Interleaved (Distributed)
        Y_IFDMA = Y_IFDMA(1:Q:N);                % IFDMA subcarrier demapping
        H_demap = H(1:Q:N);      % Channel response for IFDMA subcarriers

        %Y_IFDMA = Y_IFDMA./H_demap;                    % Equalization (ZF)

        E = conj(H_demap)./(conj(H_demap).*H_demap + 10^(-snrdB(n)/10));
        Y_IFDMA = Y_IFDMA.*E;                         % Equalization (MMSE)

        % Localized
        Y_LFDMA = Y_LFDMA(1:M);                  % LFDMA subcarrier demapping
        H_demap = H(1:M);        % Channel response for LFDMA subcarriers

        %Y_LFDMA = Y_LFDMA./H_demap;                    % Equalization (ZF)

        E = conj(H_demap)./(conj(H_demap).*H_demap + 10^(-snrdB(n)/10));
        Y_LFDMA = Y_LFDMA.*E;                         % Equalization (MMSE)

        %%%%%%%%%%%%%%%%%%%%% M-POINT IFFT %%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        % Estimated Symbols
        EstSymbols_IFDMA = ifft(Y_IFDMA);
        EstSymbols_LFDMA = ifft(Y_LFDMA);

        %%%%%%%%%%%%%%%%%% OUTPUT DATA + DETECTION %%%%%%%%%%%%%%%%%%%%%

        % Hard decision detection
        dataOutput_IFDMA = qamdemod(EstSymbols_IFDMA*norms(m),QAM,'gray',
        'OutputType','bit','UnitAveragePower',true).';
        dataOutput_LFDMA = qamdemod(EstSymbols_LFDMA*norms(m),QAM,'gray',
        'OutputType','bit','UnitAveragePower',true).';

        % Finds the nº of bits that differ between the Input and Output
        bits Matrix
        % Count errors:
        numerrs_IFDMA = numerrs_IFDMA +
        biterr(dataInMatrix,dataOutput_IFDMA);
        numerrs_LFDMA = numerrs_LFDMA +
        biterr(dataInMatrix,dataOutput_LFDMA);

    end

    %%%%%%%%%%%%%%%%%%%%%%% BER CALCULATION %%%%%%%%%%%%%%%%%%%%%%%%%%%

    BER_IFDMA(n) = numerrs_IFDMA/(numBits*numIterations);
    BER_LFDMA(n) = numerrs_LFDMA/(numBits*numIterations);
    [snrdB(n) BER_IFDMA(n) BER_LFDMA(n)]
    toc
end

% PLOTTING: BER vs Eb/No
figure(7)
% AWGN Theoretical Curve
ber_awgnTheory = berawgn(EbNoVec,'qam',QAM);
% Plot IFDMA Estimated Curve
semilogy(EbNoVec,BER_IFDMA,'--*r','linewidth',2)
```

```
hold on
% Plot LFDMA Estimated Curve
semilogy(EbNoVec,BER_LFDMA,'--*g','linewidth',2)
hold on
% Plot AWGN Theoretical Curve
semilogy(EbNoVec,ber_awgnTheory)
hold on
% Axis: Eb/No from 0 to 15 dB and BER from 10^-4 to 1
axis([0 15 10^-4 1])
grid
legend('Estimated IFDMA BER (Distributed)','Estimated LFDMA BER
(Localized)','Theoretical AWGN BER')
xlabel('Eb/No (dB)')
ylabel('Bit Error Rate')
title('BER vs Eb/No')
```

A.4. SCFDMA_Multiple_Users.m

```
%**************************************************************************
%                            SCFDMA_Multiple_Users
%**************************************************************************
%
%    PROJECT: OFDM Smart Beamforming
%    Author: Paul Otterstein Bolos
%
%    Operation:   SC-FDMA point-to-point Simulation:
%                 -    Signal Generation and BER simulation
%                 -    Multiple Users
%                 -    Subcarrier mapping: Localized (LFDMA)
%                 -    Channel Equalization: MMSE
%
%--------------------------------------------------------------------------
clc;
close all;

%%%%%%%%%%%%%%%%%%%%%%%%%%%% PARAMETERS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% FFT size
Nfft = 512;
% Cyclic Prefix Length (Extended CP)
Ncp = 128;
% Total number of subcarriers
N = Nfft;
% Block of M QAM data symbols (data block size)
M = 128;
% Bandwidth Spreading Factor
Q = N/M;
% Size of QAM signal constellation
QAM = input(' Enter the value of M array for QAM modulation : ');
% Number of bits per symbol
m = log2(QAM);
% Number of bits to process
numBits = m*M;
% Eb/No Vector (from 0 to 15 dB)
EbNoVec = (0:15)';
% Convert Eb/No to SNR in dB (SNR = Eb/No * m)
snrdB = EbNoVec + 10*log10(m);
```

```
% Number of simulation iterations
numIterations = 1000;
% Sampling Frequency
fs = 2*3.84e6;
% Sampling Time
Ts = 1/fs;

%%%%%%%%%%%%%%%%%%%%%%%%%%% CHANNEL %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

LTE_Channel;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% USERS
% UEs trying to connect to BS simultaneously
%U = randi([1 Q]);
U = 4;
% Start BER plot
figure(4)
% AWGN Theoretical Curve
ber_awgnTheory = berawgn(EbNoVec,'qam',QAM);
% Plot AWGN Theoretical Curve
semilogy(EbNoVec,ber_awgnTheory)
hold on

% for each user
for user = 1:U

    % Results for every EbNo <-> SNR (BER SIMULATION)
    for n = 1:length(snrdB)
        tic;
        % Initialize the error count
        numerrs = 0;

        % Results for every iteration
        for k = 1:numIterations


            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            %                          TRANSMITTER
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


            %%%%%%%%%%%%%%%%%%%%%% INPUT DATA %%%%%%%%%%%%%%%%%%%%%%%%%%

            % Incoming Bit Stream
            dataIn = randi([0 1], 1, numBits);

            % Serial to Parallel Converter
            % Reshape data into binary m-tuples
            dataInMatrix = reshape(dataIn, m, length(dataIn)/m).';

            % Bit to Constellation Mapping
            % Convert to integers (integer vector)
            dataSymbolsIn = bi2de(dataInMatrix,'left-msb').';
            % norms for BPSK 4-QAM 16-QAM...
            norms = [1 sqrt(2) 0 sqrt(10) 0 sqrt(42)];
            % Modulated source symbols (Gray Coding normalized)
            SymbolsIn = qammod(dataSymbolsIn,QAM,'gray')/norms(m);
```

```
%%%%%%%%%%%%%%%%%% M-POINT DFT SPREADING %%%%%%%%%%%%%%%%%%%

SymbolsIn_freq = fft(SymbolsIn);

%%%%%%%%%%%%%%%%%%%% SUBCARRIER MAPPING %%%%%%%%%%%%%%%%%%%%

SamplesIn = zeros(1,N);
SamplesIn(1+(user-1)*M:user*M) = SymbolsIn_freq;

%%%%%%%%%%%%%%%%%%%%%% N-POINT IFFT %%%%%%%%%%%%%%%%%%%%%%%%

% Convert the signal back to time domain
SamplesIn_ifft = ifft(SamplesIn);

%%%%%%%%%%%%%%%%%%%% ADD CYCLIC PREFIX %%%%%%%%%%%%%%%%%%%%%

TxSamples = [SamplesIn_ifft(N-Ncp+1:N) SamplesIn_ifft];


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                        CHANNEL + AWGN
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%% CHANNEL PROPAGATION %%%%%%%%%%%%%%%%%%%

RxSamples = filter(h, 1, TxSamples);     % Multipath Channel

%%%%%%%%%%%%%%%%%%%%%%% AWGN NOISE %%%%%%%%%%%%%%%%%%%%%%%%%

tmp = randn(2, N+Ncp);
complexNoise = (tmp(1,:) + 1i*tmp(2,:))/sqrt(2);
% Signal Power Transmitted
Ps = 0.199995;
noisePower = Ps*10^(-snrdB(n)/10);
RxSamples = RxSamples + sqrt(noisePower/Q)*complexNoise;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                           RECEIVER
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%% REMOVE CYCLIC PREFIX %%%%%%%%%%%%%%%%%

RxSamples = RxSamples(Ncp+1:N+Ncp);

%%%%%%%%%%%%%%%%%%%%%%% N-POINT FFT %%%%%%%%%%%%%%%%%%%%%%%%

% Convert the received signal into frequency domain
Y = fft(RxSamples, Nfft);

%%%%%%%%% SUBCARRIER DEMAPPING + EQUALIZATION (ZF) %%%%%%%%%

% Localized
Y = Y(1+(user-1)*M:user*M);
H_demap = H(1+(user-1)*M:user*M);
```

```
            Y = Y./H_demap;                          % Equalization (ZF)
            E = conj(H_demap)./(conj(H_demap).*H_demap + 10^(-
            snrdB(n)/10));
            %Y = Y.*E;                              % Equalization (MMSE)

            %%%%%%%%%%%%%%%%%%%%% M-POINT IFFT %%%%%%%%%%%%%%%%%%%%%%%%%

            % Estimated Symbols
            EstSymbols = ifft(Y);

            %%%%%%%%%%%%%%%%% OUTPUT DATA + DETECTION %%%%%%%%%%%%%%%%%%

            dataOutput = qamdemod(EstSymbols*norms(m),QAM,'gray',
           'OutputType','bit','UnitAveragePower',true).';

            % Finds the nº of bits that differ between the Input and
            Output bits Matrix
            % Count errors:
            numerrs = numerrs + biterr(dataInMatrix,dataOutput,m);

        end

        %%%%%%%%%%%%%%%%%%%%%%% BER CALCULATION %%%%%%%%%%%%%%%%%%%%%%%%

        BER(n) = numerrs/(numBits*numIterations);
        [snrdB(n) BER(n)]

        toc
    end

    % PLOTTING: BER vs Eb/No
    % Plot LFDMA Estimated Curve (user 1)
    semilogy(EbNoVec,BER,'linewidth',2)
    hold on
    grid on
    % Axis: Eb/No from 0 to 15 dB and BER from 10^-4 to 1
    axis([0 15 10^-4 1])
    xlabel('Eb/No (dB)')
    ylabel('Bit Error Rate')
    title('BER vs Eb/No')

end

if U == 1
    legend('Theoretical AWGN BER','User 1')
elseif U == 2
    legend('Theoretical AWGN BER','User 1','User 2')
elseif U == 3
    legend('Theoretical AWGN BER','User 1','User 2','User 3')
elseif U == 4
    legend('Theoretical AWGN BER','User 1','User 2','User 3','User4')
end
```

A.5. Beamforming.m

```
%************************************************************************
%                                  Beamforming
%************************************************************************
%
%   PROJECT: OFDM Smart Beamforming
%   Author: Miguel A. Lagunas
%
%   Adapts Matlab Code from CTTC for the example proposed
%
%   - Reads the geometry of a linear aperture and source scenario. From
%   this data, generates snapshots and computes data covariance matrix.
%
%------------------------------------------------------------------------

% Central frequency and velocity of propagation
fc=0.5;c=0.5;
% distance of sensors in wavelengths to the phase center
d=[0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5]; nsen=length(d);
% number of snapshots to be managed by the main program
nsnap=7680;
% Set source information
souele=[0 60 30 -30];
nsou=length(souele);
% baseband frequency of the sources >0 and <0.5
fresou=[0.25 0.183 0.32 0.10];
nana=length(fresou);
% source level in db.
soulev=[-20 -20 -20 -20];
% Converts degrees to radians
ii=sqrt(-1);
souelr=souele*(pi/180);
% Converts dB to levels
for i=1:nsou
        soule(i)=sqrt(10^(soulev(i)/10));
        pot(i)=soule(i)*soule(i);
end
for i=1:nsou
        dsou(:,i)=(2*pi*fc/c)*d';
        dsou(:,i)=dsou(:,i)*sin(souelr(i));
end
dsoun=dsou(:,2:nsou);
dsou=exp(-ii*dsou);
dsoun=exp(-ii*dsoun);
luso=size(d,2);
ecov=dsou*diag(pot,0)*dsou'+eye(luso);
% Source waveforms
souwav = subframe;
% Generates snapshots and computes covariance
sd=dsou(:,1);
cov=zeros(nsen,nsen);
snaa=[];
for i=1:nsnap
        xsna=dsou*souwav(:,i)+randn(nsen,1)-ii*randn(nsen,1);
        cov=cov+xsna*xsna';
        snaa=[snaa xsna];
end
```

```
cov=cov/nsnap;

%  Writes files .mat
% cov2.mat contains the full covariance estimate in cov and the exact
% covariance in ecov
save cov2l.mat cov ecov;
s=['Cov estimate in matrix cov and exact covariance in ecov saved in
file cov2l.mat'];
disp(s);
```

A.6. ZadoffChuSeq.m

```
function seq = ZadoffChuSeq(Np,q,Nzc)
% Base Sequence of length Np (Zadoff-Chu cyclically extended sequence)
n = 0:Np-1;
seq = exp(-1i*pi*q.*mod(Nzc,n).*(mod(Nzc,n)+1)/Nzc);
end
```

A.7. SCFDMA_Subframe.m

```
%*************************************************************************
%                                 SCFDMA_Subframe
%*************************************************************************
%
%   PROJECT: OFDM Smart Beamforming
%   Author: Paul Otterstein Bolos
%
%   Operation:  SC-FDMA Subframe Generation
%
%-------------------------------------------------------------------------

%%%%%%%%%%%%%%%%%%%%%%%%%%% PARAMETERS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Nfft = 512;
Ncp = 128;
N = Nfft;
M = 128;
Q = N/M;
QAM = input(' Enter the value of M array for QAM modulation : ');
m = log2(QAM);
numBits = m*M;
U = Q;

for i=1:2

    slot = [];

    for symbols=1:Nsymb

        dataIn = randi([0 1], 1, numBits);
        dataInMatrix = reshape(dataIn, m, length(dataIn)/m).';
        dataSymbolsIn = bi2de(dataInMatrix,'left-msb').';
        norms = [1 sqrt(2) 0 sqrt(10) 0 sqrt(42)];
        SymbolsIn = qammod(dataSymbolsIn,QAM,'gray')/norms(m);
```

```
        SymbolsIn_freq = fft(SymbolsIn);
        TxSymbol = [];

        % for each user
        for user = 1:U

            SamplesIn = zeros(1,N);
            SamplesIn(1+(user-1)*M:user*M) = SymbolsIn_freq;

            SamplesIn_ifft = ifft(SamplesIn);

            TxSymbol = [TxSymbol; SamplesIn_ifft(N-Ncp+1:N)
            SamplesIn_ifft];

        end

        if symbols == 3
            % Pilot Symbol
            slot = [slot [z_time;z_time;z_time;z_time]];
        else
            % Data Symbol
            slot = [slot TxSymbol];
        end
    end

    subframe = [slot slot];

end
```

A.8. RS_Uplink.m

```
%*************************************************************************
%                                RS_Uplink
%*************************************************************************
%
%   PROJECT: OFDM Smart Beamforming
%   Author: Paul Otterstein Bolos
%
%   Operation: LTE Reference Signal in Uplink
%
%   Generates pilots to:
%   -   Calculate and save the data covariance matrix to visualize the
%       Beamforming calling to MI_BEAM2L.m
%   -   Calculate and save the Wiener filter weights for the Channel
%       Estimation
%
%   STEPS:
%   1.- RS Sequence Generation
%   2.- Time-Domain RS
%   3.- Create SCFDMA subframe (received)
%   4.- Cyclic Shifts of the Sequence (DM-RS) - SDMA
%   5.- Wiener's Solution
%
%-------------------------------------------------------------------------
clc;
close all;
clear all;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%% PARAMETERS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Zaddoff-Chu sequence Length (largest prime number < Np)
Nzc = 293;
% Root of the Zadoff-Chu sequence
q = 25;
% FFT size
N = 512;
% Cyclic Prefix Length (Extended CP)
Ncp = 128;
% Number of resource blocks
NULRB = 25;
% Number of subcarriers per RB
NSCRB = 12;
% RS sequence length (300)
Np = NSCRB*NULRB;
% SC-FDMA symbols in one uplink slot (Extended CP) (12 symbols/subframe)
Nsymb = 6;
% Number of transmission antennas
NTxAnts = 4;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                        1. RS SEQUENCE GENERATION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Base Sequence of length Np (Zadoff-Chu cyclically extended sequence)
z = ZadoffChuSeq(Np,q,Nzc);

figure(1)
plot(abs(xcorr(z)./length(z)));
xlabel('n');
ylabel('Absolute values');
title('Cross-correlation of RS sequence');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                        2. TIME-DOMAIN RS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Serial to Parallel Converter
z_s2p = z';

% N point IFFT
z_ifft = ifft(z_s2p,N);

% Add Cyclic Prefix
z_time = [z_ifft(N-Ncp+1:N);z_ifft];

% Parallel to Serial Converter
z_time = z_time';

save pilot.mat z_time;

figure(2)
stem(real(z_time));
xlabel('Time (Samples)');
ylabel('Magnitude');
title('Time-domain Reference Signal');
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                   3. CREATE SCFDMA SUBFRAME
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Generates SCFDMA Subframe
SCFDMA_Subframe;

figure(3)

subplot(2,2,1)
plot(abs(subframe(1,:)))
xlabel('Time (samples)')
ylabel('Magnitude')
title('Transmitted Subframe 1st User')

subplot(2,2,2)
plot(abs(subframe(2,:)))
xlabel('Time (samples)')
ylabel('Magnitude')
title('Transmitted Subframe 2nd User')

subplot(2,2,3)
plot(abs(subframe(3,:)))
xlabel('Time (samples)')
ylabel('Magnitude')
title('Transmitted Subframe 3rd User')

subplot(2,2,4)
plot(abs(subframe(4,:)))
xlabel('Time (samples)')
ylabel('Magnitude')
title('Transmitted Subframe 4th User')


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%               4. CYCLIC SHIFTS OF THE SEQ (DM-RS) - SDMA
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Cyclic shift value used for DM-RS
CyclicShift = length(z_time)/NTxAnts;

z1 = z_time(1:CyclicShift);
z2 = z_time(CyclicShift+1:2*CyclicShift);
z3 = z_time(2*CyclicShift+1:3*CyclicShift);
z4 = z_time(3*CyclicShift+1:4*CyclicShift);

zn = [z1' z2' z3' z4'];


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                       5. WIENER'S SOLUTION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Calls script from CTTC software (generates snapshots & computes data
covariance matrix)
Beamforming;
```

```
% Snapshots Xn generated (n=1...N)
snapshot = snaa;
% Covariance matrix of the snapshots
R = cov;
% Initiate p vector
p1 = zeros(nsen,1);
p2 = zeros(nsen,1);
p3 = zeros(nsen,1);
p4 = zeros(nsen,1);

for mean=1:nsnap
    for i=1:length(z1)
% Cross-correlation between the snapshot and the reference signal
        p1 = p1 + conj(z1(i))*snapshot(:,mean);
        p2 = p2 + conj(z2(i))*snapshot(:,mean);
        p3 = p3 + conj(z3(i))*snapshot(:,mean);
        p4 = p4 + conj(z4(i))*snapshot(:,mean);
    end
end

% Average
p1 = p1/nsnap;
p2 = p2/nsnap;
p3 = p3/nsnap;
p4 = p4/nsnap;

% Wiener's solution: wopt = R^-1 * p
w_opt1 = R\p1;
w_opt2 = R\p2;
w_opt3 = R\p3;
w_opt4 = R\p4;

w_opt = [w_opt1 w_opt2 w_opt3 w_opt4];
save wiener.mat w_opt;

figure(4)
subplot(2,2,1)
stem(abs(w_opt1))
title('Wiener 1st User')
subplot(2,2,2)
stem(abs(w_opt2))
title('Wiener 2nd User')
subplot(2,2,3)
stem(abs(w_opt3))
title('Wiener 3rd User')
subplot(2,2,4)
stem(abs(w_opt4))
title('Wiener 4th User')

% Create 1-d beamformers for linear arrays and plot their response
% Steering vector for the desired source - Change value
sd=exp(-ii*(2*pi*fc/c)*d'*sin(souelr(4)));
ndibs=250;
xxe=-90:180/ndibs:90;
xx=xxe*pi/180;
xx=sin(xx);
sx=exp(-ii*(2*pi*fc/c)*d'*xx);
arr=inv(cov)*sd;
stri=['Beamforming'];
per=pattern(arr,stri,sx,xxe,souele,soulev,2);
```

A.9. pattern.m

```
%
%   File PATTERN.M
%
%
%  Miguel A. Lagunas            Marzo 1996
%
%.................................................................
function [pr]=pattern(zp,stri,sx,xxe,souele,soulev,aa)
figure(aa);
clf;
nsou=length(souele);
aro=sin(souele*pi/180);
%
zpat=10*log10(abs(sx'*zp));
% Define the floor for the plot as -30 dB. below the maximum source
level
zfloor=max(zpat)-30;
for i=1:length(xxe)
    if zpat(i)<zfloor
        zpat(i)=zfloor;
    end
end
plot(xxe,zpat,'k');
hold on;
grid;
ylabel('Array factor (dB)');
xlabel('Elevation (º)');title(stri);
% Plot the actual source location
au=min(zpat);
bu=max(zpat);
zref=zfloor*ones(size(zpat));
for i=1:length(xxe)
  for l=1:nsou
    if xxe(i)<=souele(l)
      if xxe(i+1)>souele(l)
              zref(i)=soulev(l);
      end
    end
  end
end
plot(xxe,zref,'b');hold off;
axis([min(xxe),max(xxe),zfloor,max(zpat)]);
pause(0.1);pr=1;
%_________________________________________________________________________
```

A.10. Channel_Estimation.m

```
%-----------------------------------------------------------------------
% The function calculates channel estimation from the pilot signal
% generation (SC-FDMA performance)
%   -> yp: received signal of the pilot symbol
%   -> p: pilot symbol
%   -> wk: Wiener Filter
%-----------------------------------------------------------------------
function chEst = Channel_Estimation(yp, wk, N)

    b = filter(wk,1,yp);
    chEst = fft(b,N);

end
```

A.11. SCFDMA_TRB.m

```
%***********************************************************************
%                                 SCFDMA_TRB
%***********************************************************************
%
%   PROJECT: OFDM Smart Beamforming
%   Author: Paul Otterstein Bolos
%
%   Operation:  SC-FDMA Time Reference Beamforming Simulation:
%               -   Signal Generation and BER simulation
%               -   Multiple Users
%               -   Subcarrier mapping: Localized (LFDMA)
%               -   Channel Estimation Equalization
%
%-----------------------------------------------------------------------
clc;
close all;

%%%%%%%%%%%%%%%%%%%%%%%%%%%% PARAMETERS %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

BW = 5;
Nfft = 512;
Ncp = 128;
N = Nfft;
M = 128;
Q = N/M;
QAM = input(' Enter the value of M array for QAM modulation : ');
m = log2(QAM);
numBits = m*M;
EbNoVec = (0:15)';
snrdB = EbNoVec + 10*log10(m);
numIterations = 1000;
fs = 2*3.84e6;
Ts = 1/fs;

%%%%%%%%%%%%%%%%%%%%%%%%%%%% CHANNEL %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
LTE_Channel;
```

```
% USERS
U = randi([1 Q]);

% Start BER plot
figure(4)
ber_awgnTheory = berawgn(EbNoVec,'qam',QAM);
semilogy(EbNoVec,ber_awgnTheory
hold on

% for each user
for user = 1:U

    % Results for every EbNo <-> SNR (BER SIMULATION)
    for n = 1:length(snrdB)
        tic;
        % Initialize the error count
        numerrs = 0;

        % Results for every iteration
        for k = 1:numIterations


            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            %                          TRANSMITTER
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


            %%%%%%%%%%%%%%%%%%%%%% INPUT DATA %%%%%%%%%%%%%%%%%%%%%%%%%%

            % Incoming Bit Stream
            dataIn = randi([0 1], 1, numBits);

            % Serial to Parallel Converter
            dataInMatrix = reshape(dataIn, m, length(dataIn)/m).';

            % Bit to Constellation Mapping
            dataSymbolsIn = bi2de(dataInMatrix,'left-msb').';
            norms = [1 sqrt(2) 0 sqrt(10) 0 sqrt(42)];
            SymbolsIn = qammod(dataSymbolsIn,QAM,'gray')/norms(m);

            %%%%%%%%%%%%%%%%%% M-POINT DFT SPREADING %%%%%%%%%%%%%%%%%%%

            SymbolsIn_freq = fft(SymbolsIn);

            %%%%%%%%%%%%%%%%%%%% SUBCARRIER MAPPING %%%%%%%%%%%%%%%%%%%%

            SamplesIn = zeros(1,N);
            SamplesIn(1+(user-1)*M:user*M) = SymbolsIn_freq;

            %%%%%%%%%%%%%%%%%%%%%% N-POINT IFFT %%%%%%%%%%%%%%%%%%%%%%%%

            % Convert the signal back to time domain
            SamplesIn_ifft = ifft(SamplesIn);

            %%%%%%%%%%%%%%%%%%%% ADD CYCLIC PREFIX %%%%%%%%%%%%%%%%%%%%%

            TxSamples = [SamplesIn_ifft(N-Ncp+1:N) SamplesIn_ifft];
            load pilot.mat;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                         CHANNEL + AWGN
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%% CHANNEL PROPAGATION %%%%%%%%%%%%%%%%%%%

RxSamples = filter(h, 1, TxSamples);
% Received signal of the pilot symbol
yp = filter(h,1,z_time);

%%%%%%%%%%%%%%%%%%%%%%% AWGN NOISE %%%%%%%%%%%%%%%%%%%%%%%%%

tmp = randn(2, N+Ncp);
complexNoise = (tmp(1,:) + 1i*tmp(2,:))/sqrt(2);
Ps = 1;
noisePower = Ps*10^(-snrdB(n)/10);
RxSamples = RxSamples + sqrt(noisePower/Q)*complexNoise;
yp = yp + sqrt(noisePower)*complexNoise;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                            RECEIVER
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

load wiener.mat;
RxSamples = RxSamples.*w_opt(:,user);
%%%%%%%%%%%%%%%%%%%%% REMOVE CYCLIC PREFIX %%%%%%%%%%%%%%%%%

RxSamples = RxSamples(Ncp+1:N+Ncp);

%%%%%%%%%%%%%%%%%%%%%%% N-POINT FFT %%%%%%%%%%%%%%%%%%%%%%%%

% Convert the received signal into frequency domain
Y = fft(RxSamples, Nfft);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                    SUBCARRIER DEMAPPING
%                            +
%            CHANNEL ESTIMATION EQUALIZATION (ZF)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Localized
Y = Y(1+(user-1)*M:user*M);

% Channel estimation for each user
chEst = Channel_Estimation(yp,w_opt(:,user),M);
H_demap = chEst;
Y = Y./H_demap;

%%%%%%%%%%%%%%%%%%%%% M-POINT IFFT %%%%%%%%%%%%%%%%%%%%%%%%%

% Estimated Symbols
EstSymbols = ifft(Y);

%%%%%%%%%%%%%%%%% OUTPUT DATA + DETECTION %%%%%%%%%%%%%%%%%%

dataOutput = qamdemod(EstSymbols*norms(m),QAM,'gray',
```

```
            'OutputType','bit','UnitAveragePower',true).';

            % Finds the nº of bits that differ between the Input and
            Output bits Matrix
            % Count errors:
            numerrs = numerrs + biterr(dataInMatrix,dataOutput,m);

        end

        %%%%%%%%%%%%%%%%%%%%%%% BER CALCULATION %%%%%%%%%%%%%%%%%%%%%%%%

        BER(n) = numerrs/(numBits*numIterations);
        [snrdB(n) BER(n)]

        toc
    end

    % PLOTTING: BER vs Eb/No
    % Plot LFDMA Estimated Curve (user 1)
    semilogy(EbNoVec,BER,'linewidth',2)
    hold on
    axis([0 15 10^-4 1])
    xlabel('Eb/No (dB)')
    ylabel('Bit Error Rate')
    title('BER vs Eb/No')

end

if U == 1
    legend('Theoretical AWGN BER','User 1')
elseif U == 2
    legend('Theoretical AWGN BER','User 1','User 2')
elseif U == 3
    legend('Theoretical AWGN BER','User 1','User 2','User 3')
elseif U == 4
    legend('Theoretical AWGN BER','User 1','User 2','User 3','User4')
end
```

Glossary

3GPP	Third Generation Partnership Project
4G	Fourth-Generation Wireless Systems
BER	Bit Error Rate
BS	Base Station
CAZAC	Constant Amplitude Zero Autocorrelation
CE	Channel Estimation
CP	Cyclic Prefix
CS	Cyclic Shift
CTTC	Centre Tecnològic de Telecomunicacions de Catalunya
DFDMA	Distributed Frequency Division Multiple Access
DFT	Discrete Fourier Transform
DM-RS	Demodulation Reference Signals
EPA	Extended Pedestrian A model
ETU	Extended Typical Urban model
EVA	Extended Vehicular A model
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
IFFT	Inverse Fast Fourier Transform
IFDMA	Interleaved Frequency Division Multiple Access
ISI	Inter Symbol Interference
LFDMA	Localized Frequency Division Multiple Access
LTE	Long Term Evolution
MDIR	Matched Desired Impulse Response
MIMO	Multiple-Input Multiple-Output
MMSE	Minimum Mean Square Error
MSE	Minimum Square Error
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access

PAPR	Peak-to-Average Power Ratio
P/S	Serial-to-Parallel
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
RS	Reference Signal
SC-FDMA	Single Carrier-Frequency Division Multiple Access
SDMA	Space-Division Multiple Access
SNR	Signal to Noise Ratio
S/P	Serial-to-Parallel
SRB	Spatial Reference Beamforming
SRS	Sounding Reference Signal
TDD	Time Division Duplex
TRB	Time Reference Beamforming
TTI	Transmission Time Interval
UE	User Equipment
ZC	Zadoff-Chu
ZF	Zero Forcing